School of Civil and Mechanical Engineering
Department of Civil Engineering

Durability of Fly Ash Based Geopolymer Concrete

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This thesis is presented for the Degree of
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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

The following publications have resulted from the work carried out for this degree.

Publications:

1. Deb, P. S., Nath, P. and Sarker, P. K. (2013). Strength and Permeation Properties of Slag Blended Fly Ash Based Geopolymer Concrete. *Advanced Materials Research*, 651, 168-173.

2. Deb, P. S., Nath, P. and Sarker, P. K. (2013). PROPERTIES OF FLY ASH AND SLAG BLENDED GEOPOLYMER CONCRETE CURED AT AMBIENT TEMPERATURE. Accepted for the *7th International Structural Engineering and Construction Conference (ISEC-7)*, Honolulu, USA, June 18-23.

3. Deb, P. S., Nath, P. and Sarker, P. K. (2013). Properties of Slag Blended Fly Ash Based Geopolymer Concrete in Aggressive Environment. Paper submitted to the *26th Biennial Concrete Institute of Australia's National Conference* (Concrete 2013), Gold Coast Convention and Exhibition Centre, Queensland from 16 to 18 October.

ABSTRACT

Geopolymer is a binder that can act as an alternative to Portland cement. Utilization of geopolymer concrete as an alternative material adds sustainability to the environment by reducing the greenhouse gas emission associated with cement production. The properties of concrete using fly ash based geopolymer as the binder were shown in recent studies. However, most of the previous studies focused on the properties of geopolymer concrete samples cured at high temperature. In this study, fly ash based geopolymer concrete suitable for curing at ambient temperature was designed. The mixture proportions used in this study were developed based on the constant total binder content of 400 Kg/m^3. Two different mixtures (series A and B) with 40% and 35% alkaline activator and ground granulated blast furnace slag (GGBFS) in different proportions with fly ash were used for the geopolymer concrete specimens. Two mixtures with ordinary Portland cement were also designed following the ACI211.1-91 guidelines. After casting, the geopolymer concrete samples were cured at ambient condition of the laboratory (15-20^{0}C and 60±10% RH) until the test and the OPC concrete samples were cured under lime water up to 28 days. Ten geopolymer concrete (four mixtures for series A and 6 for series B) and two OPC concrete mixtures were prepared in laboratory to study the properties of geopolymer concrete. It is found from the study that the incorporation of GGBFS in fly-ash based geopolymer concrete has a significant effect on the development of mechanical and durability properties. The mechanical properties of the concrete were investigated by compressive strength, tensile strength and flexural strength. The investigated durability properties were the drying shrinkage, sorptivity, volume of permeable voids (VPV) and effects of the exposure of different aggressive environments such as sodium sulphate solution, alternative wetting and drying in salt-water environment. The geopolymer concrete compressive strength at 28 days varied from 27 to 55 MPa. The ultimate strength of slag blended fly ash based geopolymer concretes reached up to 70MPa. The geopolymer concretes showed drying shrinkage, sorptivity and VPV values comparable to those of the OPC concrete of similar compressive strength. Moreover, the slag blended fly ash-based geopolymer concrete exhibited an excellent resistance to sulphate attack and alternate wetting and drying effect. The resistance to aggressive environment increased with the increase of slag content in the mixtures. There was no sign of crack or any significant change in the mass of the geopolymer concrete samples after exposure to the aggressive environment. The geopolymer concrete samples showed low expansions in sulphate solution. In general, blending of slag with fly ash in geopolymer concrete improved strength and performed satisfactorily in aggressive environments when cured in ambient temperature.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	Mass of oven-dry test sample in air	gm
A	Cross sectional area	mm^2
B	Mass of saturated-surface-dry test sample in air	gm
B	Average width of the specimen at the section of failure	mm
C	Apparent mass of saturated test sample in water	gm
D	Diameter of the specimens	mm
D	Average depth of specimen at the section of failure	mm
D	The density of the water	gm/mm^3
f_c	Compressive strength	MPa
f'_{cr}	Required average compressive strength	MPa
f_{ct}	Indirect tensile Strength	MPa
f_{cf}	Modulus of rupture	MPa
G	Mass of the aggregate plus the measure	kg
I	Absorption	mm
K	Empirical factor	-
L	Length of the specimens'	mm
L_{ds}	Drying shrinkage	microstrain
L_t	Length of the individual specimen at any specified time t	mm
L_i	Initial length of the individual specimen	mm
M	Bulk density of the aggregate	kg/m^3
M_t	The change in specimen mass in grams, at the time t	gm
M_1	Weight of the oven dried samples	gm
M_{2i}	Saturated weight after immersion	gm
M_{3b}	Weight of the sample after boiling and cooling	gm
M4ib	Weight of the sample suspended in the water	gm

P	Maximum force applied	kN
P	Average compressive strength of reference cement mortar cubes	MPa (psi).
SP	Average compressive strength of slag-reference cement mortar cubes	MPa(psi)
S	Mass of saturated surface dry sample	gm
SS/SH	Sodium silicate to sodium hydroxide ratio	-
T	Mass of the measure	kg
V	Volume of the measure	m^3
W/C	Water cement ratio	-
W/S	Water solid ratio	-

ABBREVIATIONS

AAR	Alkali aggregate reaction
ACI	American concrete of institute
AS	Australian standard
ASR	Alkali-silica reaction
ASTM	American society for testing materials
BS	British standard
GGBFS	Grand granular blast furnace slag
HSC	High strength concrete
HVFA	High volume fly ash
LOI	Loss of ignition
OPC	Ordinary Portland cement
SEM	Scanning electron microscope
SSD	Saturated surface dry
VPV	Volume of permeable voids
XRF	X-Ray florescence

1. INTRODUCTION

1.1. Background

Geopolymer is a rising field of research for utilizing by-products. It has paved the way for finding new alternatives for the replacement of cement in the concrete industry and may be utilized by cement producers to offer a broader range of cementitious products to the market.

Geopolymers are members of the family of inorganic alumino-silicate polymer synthesized from alkaline activation of various aluminosilicate materials or other by-product materials like fly ash, metakaoline, blast furnace slag etc. (Davidovits, 2008). The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous. The final products of geopolymerisation are influenced by several factors based on chemical composition of the source materials and alkaline activators (Diaz et al. 2010; Yip et al. 2008). The polymerisation process is generally accelerated at higher temperatures. Fly ash based geopolymer produced in ambient temperature achieve lower strength in early days as compared to heat-cured specimens (Vijai et al. 2010).

Heat-cured fly ash based geopolymer concrete has high compressive and tensile strengths, and low effective porosity, which are all beneficial for concrete in an aggressive environment (Olivia and Nikraz, 2011). Most of the previous studies were conducted on heat-cured geopolymer concrete that is considered to be ideal for precast concrete members. However, geopolymer concrete produced without using elevated heat for curing will widen its application to the areas beyond precast members.

In this work, ground granulated blast furnace slag (GGBFS) is used together with fly ash as a part of the total binder. The GGBFS blended fly ash-based geopolymer paste binds the aggregates to form the geopolymer concrete, with or without the presence of admixtures. GGBFS was added with low calcium fly ash in order to accelerate the curing of geopolymer concrete in ambient temperature.

The manufacture of geopolymer concrete is carried out using the usual prctice in concrete technology.

Durability related properties are important considerations for design of concrete. Permeability characteristics are considered as the most important properties to govern durability of conrete. Lower permeability gives higher resistance to the ingress of aggressive ions into the concrete and thereby reduces the extent of deterioration of concrete. Hence, the durability properties of GGBFS blended fly ash based geopolymer concrete cured at ambient temperature were studied in this research.

1.2. Objective and Scope of work

The present study dealt with the manufacture and the durability properties of GGBFS blended fly ash-based geopolymer concrete. The primary objectives of this research are as follows:

- Study the durability properties of geopolymer concrete for ambient curing condition. The properties include drying shrinkage, sorptivity, VPV, resistance to sulphte attack and effect of alternate wetting and drying in sodium chloride water environment.
- Study the effect of different proportions of GGBFS in the binder on mechanical properties of geopolymer concrete in aggressive environment.
- Assess the effect of GGBFS inclusion in different proportions for different ratios of sodium silicate and sodium hydroxide in the geopolymer mixtures.
- Comparing the durability test results of geopolymer concrete with those of Portland cement concrete of the similar strength. .

1.3. Significance

Geopolymer concrete has significant advantages over the standard OPC concretes and can play a vital role in the context of sustainability and environmental issues. Development of geopolymer concrete has the potential to reduce the cement

production which in turn will reduce the greenhouse gas emissions. Manufacture of geopolymer concrete can reduce the CO_2 emission almost by 80% as compared to the manufacture of Portland cement based concrete (Duxson et al., 2007).

Geopolymer concrete structural members can be produced using the existing methods used for OPC concrete members. However, some extra constituents (alkali additives) are necessary to add for enhancement of the setting and strength development characteristics of fly ash based geopolymer concrete. The most common alkaline activator used in geopolymerisation is a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Moreover, heat-cured concrete requires controlled curing environment to achieve the desired mechanical and durability properties. The results of this study will be useful for design of geopolymer concrete for ambient curing conditions. Influences of the important variables in slag blended fly ash based geopolymer concrete cured at ambient condition have been studied. Workability of the fresh concrete mixtures and some mechanical and durability properties after hardening have been investigated. The results of this study will help promote in-situ casting of geopolymer concrete in sustainable concrete construction applications.

1.4. Organization of Thesis

Chapter 1 presents the objectives, scopes and significance of the current study.

Chapter 2 gives the introduction of geopolymer concrete and the previous research on geopolymer technology. The factors affecting the durability of geopolymer concrete are also described.

Chapter 3 presents the experimental work consisting of materials used, testing methodology and the set up used to carry out the tests.

Chapter 4 presents and discusses the results of the experimental work.

Chapter 5 summarises the study and draws conclusions from the results.

1.5. Summary

Geopolymer is an inorganic binder which can be used as an alternative to cement for manufacture of concrete. Most of the published research on geopolymer concrete is on heat cured concrete. Development of geopolymer concrete for ambient curing condition is essential in order to widen its applications to industry. The present study is on the influence of several parameters on the strength and durability properties of geopolymer concrete when cured in ambient temperature. Manufacture of geopolymer concrete using low-calcium (Class F) fly ash with different amounts of GGBFS and the properties of this concrete are studied in this research

2. LITERATURE REVIEW

2.1. Introduction

Geopolymer concrete can play a vital role in the context of sustainability and environmental issues. Approximately 5% of global CO_2 emissions originate from the manufacturing of cement. According to Lawrence (1998) the production of 1 tonne of Portland cement produces approximately 1 tonne of CO_2 to atmosphere. On the other hand, other cementitious material such as slag has been shown to release up to 80% less greenhouse emissions than the production of conventional Portland cement (Roy & Idorn, 1982) and there are 80% to 90% less greenhouse gas emissions released in the production of fly ash (Duxson et al., 2007). Therefore a 100% replacement of OPC with GGBS or fly ash would significantly reduce the CO_2 emission of concrete production. Previous studies by Davidovits (1991), Rangan (2008) and Collins & Sanjayan (1998) showed that the development of new binders commonly known as geopolymers alternative to traditional cements can be obtained by the alkaline activation of different industrial by-products such as blast furnace slag and fly ash. Geopolymer concretes are characterised by their good mechanical properties and low CO_2 emission.

2.1.1. Pozzolanic materials

A pozzolan is defined as finely divided siliceous or aluminous material that chemically reacts with the calcium hydroxide at ordinary temperature and in the presence of moisture to form compounds possessing cementitious properties (Malhotra & Mehta, 1996). Fly ash, blast furnace slag and silica fume are the most common pozzolanic materials used in traditional cement concrete. Replacement of cement by the pozzolanic materials usually reduces the early-age strength of concrete. However, they offer improvements of various late–age properties of concrete.

2.2. Fly ash

2.2.1. Production of fly ash

In AS1379-2007 (Standards Australia, 2007), the term “cement” is defined as a hydraulic binder composed of Portland or blended cement used alone or combined with one or more supplementary cementitious materials. Fly ash, therefore, fits within the definition of cement in AS1379-2007 (Standards Australia, 2007) and can be incorporated into normal or special class concrete either as a blended cement, or added directly into the concrete at a batch production facility.

Fly ash has pozzalonic properties. It is commonly known as a supplementary cementitious material. Fly ash is a fine grey powder consisting mostly of spherical glassy particles. Figure 2-1 shows a typical microscopic picture of fly ash particles, taken by a scanning electron microscope (SEM).

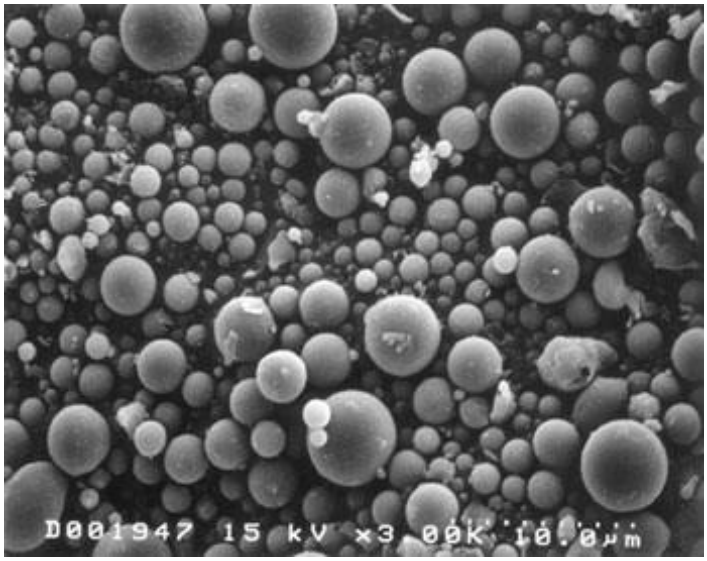


Figure 2-1: Fly ash particles magnification
taken using a scanning electron microscope (fly ash particles, 2012)

Fly ash is generally produced by coal-fired electric and steam generating plants. Typically, coal is pulverized and blown with air into the boiler's combustion chamber where it immediately ignites, generating heat and producing a molten mineral residue. Boiler tubes extract heat from the boiler, cooling the flue gas and causing the molten mineral residue to harden and form ash. Coarse ash particles,

referred to as bottom ash, fall to the bottom of the combustion chamber, while the lighter fine ash particles, termed as fly ash, remain suspended in the flue gas. Prior to exhausting the flue gas, fly ash is removed by particulate emission control devices, such as electrostatic precipitators or filter fabric bag houses (Figure 2.2).

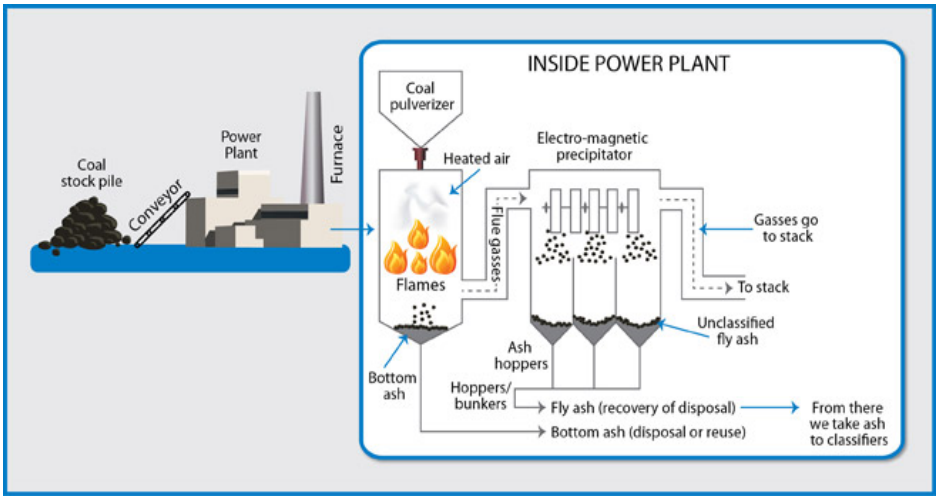


Figure 2-2: The process of producing of fly ash in a power plant (Sephaku Ash's facility, 2013).

2.2.2. Use of fly ash in concrete.

With the availability of quality fly ashes in Australia, significant benefits have been derived through optimising fly ash contents in concretes (Khatri and Sirivivatnanon, 2001). Use of fly ash in Portland cement concrete can be beneficial to reduce permeability to water and aggressive agents. Properly cured concrete made with fly ash creates a denser product because the sizes of the pores are reduced by the reaction product of fly ash. Consequently, this increases strength and reduces permeability.

A reduction in the amount of mixing water of concrete can be obtained due to the spherical shape of the fly ash particles. Moreover, concrete placement characteristic can be improved significantly by using fly ash in the concrete mixtures (Baweja et al., 1998; Samarin et al., 1983). In precast concrete, the benefit of fly ash can be translated into better workability, resulting in sharp and distinctive corners and edges with a better surface appearance. Fly ash also

benefits precast concrete by reducing permeability. The use of fly ash can result in better workability, cohesiveness, ultimate strength and durability. Added to this, the fine particles in fly ash can help to reduce bleeding and segregation which lead to improve the pumpability and finishing properties, especially in lean mixes.
The use of fly ash in concrete can lead to many improvements in overall concrete performance. Up to 60% of cement can be replaced by fly ash in high volume fly ash (HVFA) concrete which showed excellent mechanical properties with enhanced durability performance. HVFA concrete has been proved to be more durable and resource-efficient than the OPC concrete (Malhotra 2002).

2.2.3. Fly ash as a source material for geopolymers

Two major classes of fly ash are specified in ASTM C 618-12 (ASTM standard, 2012c) on the basis of their chemical composition resulting from the type of coal burned; these are designated class F and class C. Class F is fly ash normally produced from burning anthracite or bituminous coal, and class C is normally produced from the burning of subbituminous coal and lignite (Halstead, 1986). Primary difference between class C and class F fly ash as per the ASTM standard is the amount of calcium, silica, alumina, and iron content in the ash. The CaO content in class F fly ash is less than 20%. On the other hand, class C fly ash has lower silica and alumina content, but higher CaO content (20-40 weight %) than class F. The difference in CaO concentration leads to different chemistries when fly ashes are activated in acidic or basic environment (Hemmings and Berry, 1988). The effect of high calcium concentration typically leads to the acceleration of the rate of reaction. The high CaO content of class C fly ash may result in a rapid reaction and may not be suitable for applications that require longer workability or setting time. Moreover, A percentage of unburned material lower than 5%, iron (Fe_2O_3) content not higher than 10%, the content of reactive silica between 40–50%, and the percentage of particles with size lower than 45 μm between 80 and 90% is needed to ensure the suitability of fly ash that can be used as a geopolymer source material (Fernández-Jimnez and Palomo 2003). Therefore, Class F fly ash is usually recommended and was chosen in this study.

2.3. Ground granulated blast furnace slag (GGBFS)

2.3.1. Production of slag

Ground granulated blast-furnace slag (GGBFS), sometimes simply referred to as "slag", is a glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water. GGBFS consists of silicates and aluminosilicates of calcium and other bases which is developed in a molten condition simultaneously with iron in a blast furnace (AS 3582.2—2001, Standard Australia, 2001).

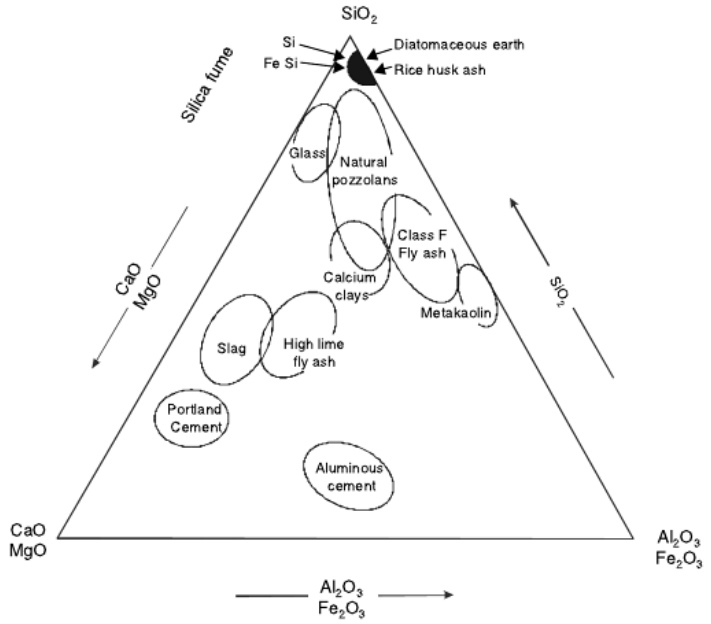


Figure 2-3: Ternary diagram of CaO-Al_2O_3-SiO_2 representing the composition of pozzolanic and cementitious materials (Aïtcin, 2008)

The main components of blast furnace slag are CaO (30-50%), SiO_2 (28-38%), Al_2O_3 (8-24%), and MgO (1-18%). Higher content of CaO in slag generally exhibit an increase in compressive strength of concrete. For a given source of GGBFS, the chemical composition remains relatively constant, especially compared to fly ash. Figure 2.3 shows the relative compositions of cementitious and different supplementary cementitious materials. Besides, use of GGBFS in concrete has advantages like low heat of hydration, high sulphate resistant and chloride ingress and higher ultimate strength.

According to ASTM C989-12 (ASTM Standard, 2012d), GGBFS is classified into three grades according to its performance in the "slag activity test". The three grades are: Grade 80, Grade 100 and Grade 120. Slag activity is determined by the following formula:

Slag activity index, % = (SP / P) × 100 ---------- (2-1)

Where,

SP = average compressive strength of slag-reference cement mortar cubes at designated ages, MPa (psi)

P = average compressive strength of reference cement mortar cubes at designated ages, MPa (psi).

2.3.2. Use of slag in concrete.

It has been generally shown that concretes containing GGBFS as a cement replacement, at normal temperatures, develop strengths at a lower rate than that made from Portland cement (Reeves, 1985 and Douglas and Zebino 1986). Those degree of decline in early age strength is a function of a number of variables. These include slag activity (Frearson and Uren, 1986 and Cook and Cao, 1987), method of proportioning and the slag content of the blend. When Portland cement and water are mixed, a chemical reaction called hydration initiates, resulting in the creation of calcium-silicate-hydrate (CSH) and calcium hydroxide (CH). CSH is a gel that is responsible for strength development in Portland cement pastes. CH is a byproduct of the hydration process that does not significantly contribute to strength development in normal Portland cement mixtures. Silicates in the slag combine with the CH by-product of hydration and form additional CSH. This in turn leads to a denser, harder binder, which increases ultimate strength as compared to 100%, Portland cement systems.

2.3.3. Geopolymer binder from slag.

Slags are by-products of metallurgical industry and consist mainly of calcium-magnesium aluminosilicate glass. The most commonly produced slags are from the iron and steel industry, called ground granulated blast-furnace slag (GGBFS). The latent hydraulic property of GGBFS makes it suitable for geopolymer binder.

Such slag with the addition of a source of alkali falls within the alkaline-alkali earth system Me_2O-MeO-Me_2O_3-SiO_2-H_2O (Krivenko, 1994). Thus, GGBFS alone can be used as a source material for geopolymer binders. However, the high CaO content of GGBFS may result in very rapid setting of the binder which may not be a suitable binder for concrete.

2.4. Geopolymer concrete

Geopolymerization is a geosynthesis–a reaction that chemically integrates minerals (Divya et al, 2007). According to Davidovits (1991), the reaction of a solid aluminosilicate with a highly concentrated aqueous alkali hydroxide or silicate solution produces a synthetic alkali aluminosilicate material generically called a 'geopolymer'. The exposure of aluminosilicate materials such as fly ash, blast furnace slag, or thermally activated substances to high-alkaline environments (hydroxides, silicates) gives rise to the formation of a geopolymer. Geopolymers are characterized by a two- to three-dimensional Si-O-Al structure.

2.4.1. Reaction mechanism of geopolymer

There are two main constituents of geopolymers, namely the source materials and the alkaline liquids. The source materials for geopolymers based on alumina-silicate should be rich in silicon (Si) and aluminium (Al). These could be natural minerals such as kaolinite, clays, etc. Alternatively, by-product materials such as fly ash, silica fume, slag, rice-husk ash, red mud etc. could be used as source materials. The choice of the source materials for making geopolymers depends on factors such as availability, cost, type of application, and specific demand of the end users. (Rangan, 2008). Figure 2-4 presents a highly simplified reaction mechanism for geopolymerization. The reaction mechanism shown in Figure 2-4 outlines the key processes occurring in the transformation of a solid aluminosilicate source into a synthetic alkali aluminosilicate.

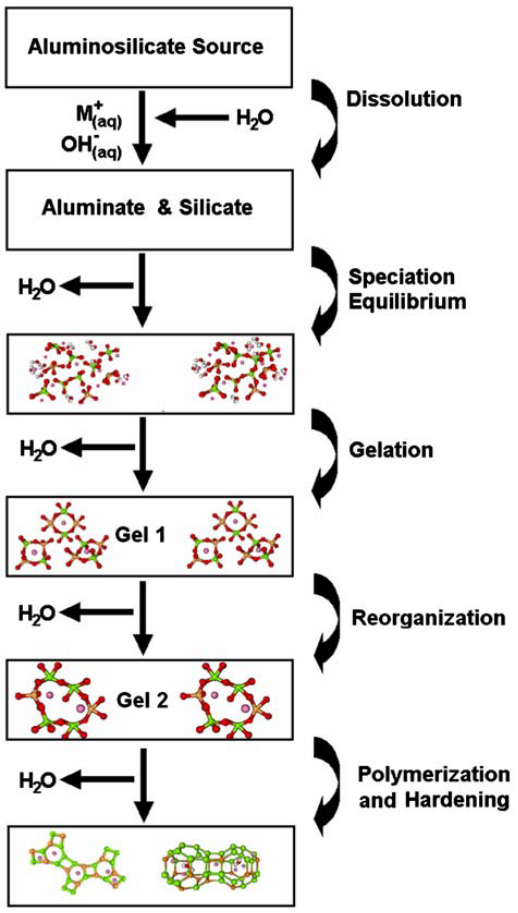


Figure 2-4: Conceptual model for geopolymerization (Duxson et al., 2007)

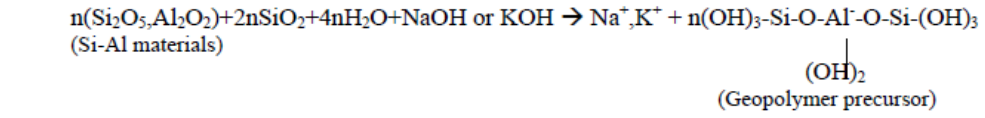
During the geopolymeriazation process, the slow growth of crystalline structures become evident as the nuclei of the polymerized gel reaches in critical size. The matrix crystallinity is relative to the rate by which precipitation occurs: fast reactions between alkali and ash do not allow time for growth of a well-structured crystalline environment. Therefore, most hardened geopolymer cements are referred to as zeolitic precursors rather than actual zeolites. The final product of geopolymerization is an amorphous, semi-crystalline cementitious material.

The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous. The polymerization process involves a substantially fast chemical reaction under alkaline conditions on Si-Al minerals, resulting in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Davidovits, 1994). The formed gel product contains alkaline cations which compensate for the deficit charges associated with

the aluminum-for-silicon substitution (Xie et al, 2001). An intermediate, aluminium-rich phase is first formed which then gives way to a more stable, silicon rich three-dimensional gel product of form Q4(nAl), which is dependent upon curing conditions and activator type (Fernandez et, al 2006).

Water is not involved in the chemical reaction of geopolymer concrete and instead water is expelled during curing and subsequent drying. This is in contrast to the hydration reactions that occur when Portland cement is mixed with water, which produce the primary hydration products calcium silicate hydrate and calcium hydroxide. This difference has a significant impact on the mechanical and chemical properties of the resulting geopolymer concrete, and also renders it more resistant to heat, water ingress, alkali–aggregate reactivity, and other types of chemical attack (Rangan, 2008).

There are several distinct reaction processes from initial pozzolanic activation to final microstructure development. The schematic formation of geopolymer material can be shown as described by Equations (2-2) and (2-3) (Davidovits, 1994; van Jaarsveld et al., 1997):



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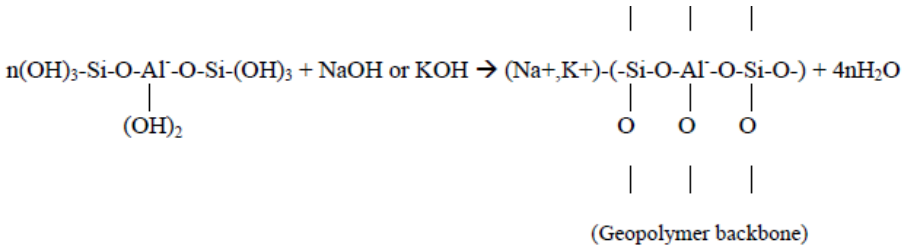


---------- (2-3)

2.4.2. Previous studies on the properties of heat cured geopolymer concrete.

During geopolymerization, once the alumino-silicate powder is mixed with the alkaline solution a paste is formed and quickly transformed into a hard

geopolymer. Therefore, there is limited time and space for the gel or paste to grow into a well crystallised structure; this is the fundamental difference between zeolites and geopolymers. After shorter setting and hardening time, geopolymers with tightly packed polycrystalline structure are formed exhibiting better mechanical properties than zeolites which have lower density and cage-like crystalline structure (Xu and Van Deventer, 2000).

Divya and Chaudhary (2007) suggest that certain synthesis limits should be used to form strong geopolymeric products. Compositions should lay in the range of 0.2– 0.48, 3.3–4.5, 10–25 and 0.8–1.6 for M_2O/SiO_2 (M represents Na/K/metallic ions), SiO_2/ Al_2O_3, H_2O/M_2O and M_2O/Al_2O_3 ratio, respectively. Most of the studies support that geopolymeric materials are prepared from alumino-silicate clay minerals and sodium silicate using restricted range of Si/Al compositions.

De Silva et al. (2007) reported that the setting time of the geopolymer systems is mainly controlled by the alumina content and increases with increasing SiO_2/Al_2O_3 ratios in the initial mixture. If the Al_2O_3 content increases (i.e. low SiO_2/Al_2O_3 ratio), the resulting products acquire low strength. Moreover, the SiO_2/M_2O ratio in an alkaline silicate solution affects the degree of polymerisation of the dissolved species (Swaddle, 2001).

Microstructure and properties of geopolymers depend strongly on the nature of the initial raw materials even though the macrocroscopic characteristics of alumino-silicate- based geopolymers may appear similar, since the same silicon and aluminum bonding and the same gel phase binder are present (Duxson et al., 2007). Through microstructural investigations it becomes clear that the ratio of the starting materials influences the homogeneity of the geopolymer microstructure, which in turn affects thermal conductivity and compressive strength (Subaer and Van Riessen, 2007).

The compressive strength of geopolymers depends on a number of factors including gel phase strength, the ratio of the gel phase/undissolved Al–Si particles, the distribution and the hardness of the undissolved Al–Si particle sizes,

the amorphous nature of geopolymers or the degree of crystallinity as well as the surface reaction between the gel phase and the undissolved Al–Si particles (Xu et al., 2000; Van Jaarsveld et al., 1997).

Wang et al. (2004) have shown experimentally that the compressive strength as well as the apparent density and the content of the amorphous phase of metakaolinite-based geopolymers, increased with the increase of NaOH concentration, within the range 4–12 mol/L. This can be attributed to the enhanced dissolution of the metakaolinite particulates and hence the accelerated condensation of the monomer in the presence of higher NaOH concentration.

Kumar et al. (2005) have shown that mechanically activated fly ash based geopolymers display higher compressive strength due to the formation of a compact microstructure. Mechanical activation of fly ash seems to favour geopolymeriation, since the reaction requires less time and takes place at lower temperature.

Moisture evaporation results in deterioration of the geopolymeric product which leads to obstruct the satisfactory strength development. Moreover, the addition of water improves the workability of the mortar (Chindaprasirt et al., 2007). However, similar geopolymer concrete mixtures without extra water exhibited higher compressive strength than the mixtures with water (Nath and Sarker 2012).

The mechanical properties of fly ash based heat-cured geopolymer concrete are comparable to OPC based concrete and the methods of calculations used in the case of reinforced Portland cement concrete beams can be used to predict the shear strength of reinforced geopolymer concrete beams (Sofi et al, 2007; Chang, 2009).

Structural performance of reinforced concrete depends on the bond between concrete and the reinforcing steel. Geopolymer concrete exhibited superior bond strength than OPC concrete and the existing design equations for bond strength of OPC concrete with steel reinforcing bars can be conservatively used for

calculation of bond strength of geopolymer concrete (Sofi et al, 2007; Sarker et al, 2007; Chang, 2009).

The behaviour and failure modes of reinforced geopolymer concrete columns and beams were similar to those observed in the case of reinforced Portland cement concrete columns (Sumajouw and Rangan, 2006; Sumajouw et al, 2007).

Durability of concrete primarily depends on its permeability characteristics. Lower permeability gives higher resistance to the ingress of aggressive ions into the concrete and thereby reduces the extent of deterioration of concrete. Heat-cured fly ash based geopolymer concrete has high compressive strength and tensile strengths, and low effective porosity, which are all beneficial for concrete in an aggressive environment (Olivia and Nikraz, 2011).

Resistance to sulphate and acidic agents is attributed to the naturally low porosity within the geopolymer matrix. Smaller entrained air voids prohibit agent mobility and yield denser, stronger cementitious product. This resistance prevents the formation of ettringite and gypsum which can lead to cracking and eventual deterioration (Wallah and Rangan, 2006). This resistance to sulphate attack makes them a prime candidate for use in sanitary sewer design and concrete culverts (Gourley and Johnson, 2005). The constant presence of deteriorating liquids and gases in sewer pipes has been found to significantly erode conventional pipe walls over extended time periods. The service life of geopolymer concretes under these conditions would be superior to pipes constructed of Portland cement.

2.5. Factors affecting the properties of geopolymers

2.5.1. Concentration of sodium hydroxide (NaOH) solution

The concentration, expressed by molarity of the activating solution determines the resulting paste properties. While high NaOH additions accelerate chemical dissolution, it depresses ettringite and CH formation during reaction (wang et al, 2004). Reduction in the CH content resulted in superior strength and durability performance (Poon et al, 2003). Furthermore, higher concentration (in terms of

molarity) of sodium hydroxide solution results in a higher compressive strength of geopolymer concrete (Hardjito et al, 2004). Additionally, the use of sodium hydroxide as an activator buffers the pH of pore fluids, regulates hydration activity and directly affects the formation of the main C-S-H product in geopolymer pastes. There is a linear relationship between NaOH concentration and the heat generation; however, there exists an inverse relationship between concentration and the time at which maximum hydration heat occurs (Chareerat et al, 2006).

2.5.2. Sodium silicate-to-sodium hydroxide liquid ratio

The addition of sodium silicates to the mix design increases mechanical properties beyond the ability of a hydroxide activator alone. However, care must be taken to regulate the ratio between each substance. Previous study indicated that the ratio of sodium silicate to sodium hydroxide plays a vital role on the development of mechanical properties of geopolymer concrete. The higher the mass ratio of sodium silicate-to-sodium hydroxide liquid, higher is the compressive strength of geopolymer concrete (Hardjito et al, 2004).

2.5.3. SiO_2 / Na_2O Ratio

The SiO_2 / Na_2O ratio is an important parameter in geopolymer design. It is well known that variations in the SiO_2 / Na_2O ratio significantly modifies the degree of polymerization of the dissolved species in the alkaline/silicate solution, thus determining the mechanics and overall properties of the synthesized gel product (Rangan, 2008). Moreover, it is noted from the previous research that A high SiO_2 / Na_2O ratio (1.6 and 2.0) was used to synthesize a geopolymer, the compressive strength was higher than a certain maximum because more geopolymer precursors formed at the maximal strength (Lin et al, 2013). Higher percentages of soluble silica in geopolymer systems retards dissolution of the ash material due to increased saturation of the ionic silica species and promotes the precipitation of larger molecular species, resulting in a stronger gel with an enhanced density (Zuda et al, 2006).

2.5.4. Water-to-geopolymer solids ratio

The water content in the mixture played an important role on the properties of geopolymer binders (Barbosa et al, 2000). The addition of any extra water in geopolymer mixtures improved the workability of the mixtures. However, the compressive strength of geopolymer concrete decreases as the ratio of water-to-geopolymer solids increases (Hardjito and Rangan, 2005). This trend is analogous to the well-known effect of water-to-cement ratio on the compressive strength of Portland cement concrete.

2.5.5. Curing time and temperature

A challenge for successful geopolymer concrete production can be obtained by proper balancing of curing time and temperatures. Similar to Portland cement, the geopolymer reaction is more easily achieved with the addition of an external heat source to promote alkaline reactivity of the pozzolanic material. Higher curing temperature resulted in larger compressive strength for geopolymer concrete (Hardjito and Rangan, 2005). Moreover, longer curing times increased the strength of alkali-activated systems, but the gain occurred at a much slower rate as time progressed due to alkaline saturation and product densification (Xie et al, 2001). The research results indicated that longer curing time improved the polymerization process resulting in higher compressive strength (Hardjito and Rangan, 2005).

2.5.6. pH Level

The strength of the geopolymer concrete can be affected by the value of pH. The pH value with a range of 13–14 was found the most suitable condition for development of good mechanical strength (Divya et al, 2007). The research also showed that an increase of the alkaline activator concentration directly raises the pH and consequently enhances the degree of reaction. Moreover, pH also plays a vital role for the viscosity of the geopolymer mixture. Lower pH value makes the mixture more stiff and viscous. On the other side higher pH makes the concrete more workable.

2.6. Some issues related to the durability of concrete

Concrete is bound by an alkaline hydrated cement paste and may be affected by acids and base substances which are usually present in industrial wastes, mine tailings and in some waters. Chemical attack by acids can be particularly severe where the pH is less than 4 and even worse where the acid solution has a velocity that is able to cause mechanical abrasion (Young et al., 1998). Chemical resistance of cement paste is directly related to its permeability, with less permeable pastes being more resistant to chemical attack. Many of the durability problems associated with ordinary Portland cement concrete arise from its calcium content in the main phases. The C_3A reacts with sulphate ions in the presence of $Ca(OH)_2$ to form ettringite and gypsum, which in turn causes expansion and degradation of the cement into a non-cohesive granular mass (Garcia-Loderio et al, 2007). However, geopolymeric materials possess low calcium containing materials that may prevent geopolymers from experiencing such negative effects.

2.6.1. Drying shrinkage

Drying shrinkage is the decrease in volume of concrete with time. Unlike creep, another long-term property of concrete, shrinkage is independent of the external actions to the concrete. Shrinkage can be divided into four types such as plastic shrinkage, chemical shrinkage, thermal shrinkage and drying shrinkage (Gilbert 2002). Previous research has reported that drying shrinkage is a direct result of hydration heat and increases with the increased dosage of waterglass activators (Fernandez et al, 2007). Moreover, it is reported by Wallah and Rangan (2006) that Heat-cured fly-ash based geopolymer concrete undergoes very low drying shrinkage. The drying shrinkage strains fluctuated slightly over the period of measurement and the value at one year measurement is only around 100 microstrain. Conversely, it was observed that ambient-cured specimens developed higher shrinkage than the heat cured fly ash based geopolymer concrete.

2.6.2. Sulphate attack

Studies of the sulphate attack on OPC concrete revealed that it has a complicated mechanism, and due to reactions between cement hydration products and sulphate-bearing solutions, it manifests itself in a variety of ways. Studies of the external sulphate attack on OPC concrete show that reactions involve CH, C–S–H and the aluminate component of hardened cement paste (Ferraris et al, 1997; Taylor, 2003). As a result of these reactions, expansion and cracking are caused, directly or indirectly, by ettringite and gypsum formation, while softening and disintegration are caused by destruction of C–S–H (Ferraris et al, 1997; Taylor, 2003, and Scrivener et al., 1995). On the other hand, Heat-cured, low calcium fly ash-based geopolymer concrete exhibits high resistance to sulphate immersion and attack. Specimens exposed to sodium sulphate for up to one year showed no visual signs of surface deterioration, cracking or spalling. Compressive strength values remained equivalent to those obtained prior to immersion. Moreover, the change in length of geopolymer samples soaked in sodium sulphate solution for various periods of exposure is very small indeed less than 0.01% of the initial geometry (Wallah and Rangan, 2006). Added to this, the best performance in different sulphate solutions was observed in the geopolymer material prepared with sodium hydroxide and cured at elevated temperature. These specimens had 4–12% increase of strength when immersed into sulphate solutions (Bakharev, 2005)

2.6.3. Alkali - aggregate reaction.

Alkali-silica reaction (ASR) is a chemical process between an alkaline solution and the aggregates involving alkaline oxides in the cement and forms of reactive silica present within the aggregate. It is a major problem of concrete durability in western part of USA and some parts of UK. In Australia, alkali aggregate reaction is not very common (Standard Australia, 1996).

The ASR expansion is more of a concern in OPC concrete due to the presence of portlandite ($Ca(OH)_2$) in the Portland cement paste. The portlandite reacts with activator alkalis (NaOH, KOH) under favourable humidity conditions to form a

gel which eventually morphs into a rigid crystalline structure causing internal expansion and deterioration of the cementitious mass (Hou et al, 2004). The water cement ratio in OPC concrete should be low to control alkali aggregate reaction since water helps alkali-silica gel to swell. Therefore, use of fly ash geopolymer concrete utilizes low liquid to solid ratio maintaining desired workability and hence can make concrete more impermeable and less vulnerable to such reaction. Moreover, Patil and Allouche (2011) observed that the fly ash based geopolymer concrete is significantly less vulnerable to ASR compared with OPC-based concrete. OPC concrete exhibited higher average expansion by a factor of 6 as compared to geopolymer concrete samples after 34 days of exposure to NaOH.

2.6.4. Heat resistance

Slag based geopolymer concretes present some technological advantages over ordinary Portland cements. These include the development of earlier and higher mechanical strengths, lower hydration heat, better resistance to chemical attack and better resistance to heat. Fly ash based geopolymer concrete can endure considerably high temperature heat. While OPC concrete degrades and degenerates at high temperature, it has been found from different study that fly ash geopolymer concrete can maintain its desired compressive strength at 400 degree centigrade. Moreover, it is observed by Zuda et al, (2006) that the alkali-activated aluminosilicate material is found to have a very good resistance to high temperature heat. The combination of two positive effects such as the formation and subsequent crystallization of akermanite and the formation of ceramic bonds creates a new structure which is responsible for the structure compaction indicated by the sudden decrease in porosity and is manifested in quite remarkable improvement of mechanical properties.

2.6.5. Alternate wetting and drying.

Cyclic wetting and drying causes continuous moisture movement through concrete pores (Crumpton, et al., 1989). This cyclic effect accelerates durability problems because it subjects the concrete to the motion and accumulation of harmful materials, such as sulphates, alkalis, acids and chlorides. Water is

evaporated due to cyclic wetting and drying and increases the concentrations of ions such as chlorides and other ions in the concrete. The drying of concrete also helps to increase the availability of the oxygen required for steel corrosion, as oxygen has a substantially lower diffusion coefficient in saturated concrete. As the concrete dries and the pores become less saturated, oxygen will have a better chance to diffuse into the concrete and attain the level necessary to induce and sustain corrosion. For example; concrete structures subjected to seawater wetting and drying exposure are most prone to deterioration, compared to concrete structures permanently submerged in seawater (Abdul-Hamid, et al, 1990).

Fly ash geopolymers have greater durability than Ordinary Portland Cement (OPC) in such severe environments, which can be attributed to their lower calcium content. Calcium is a major component of OPC that reacts with the aggressive sulphates and acids. It was summarized by Olivia and Nikraz (2012) that heat cured geopolymer concrete had a higher strength and small expansion following exposure to wetting-drying cycles.

2.7. Summary

Information available in literature that is relevant to the topic is presented in this chapter. The effect of mix design parameters on the mechanical and durabiluity properties of geopolymer concrete obtained from previous studies are gathered and critically discussed. It has been identified that there is a gap of research in the area of geopolymer concrete for ambient curing condition. Therefore, experimental work has been designed to study the durability related properties of geopolymer concrete cured at ambient temperature.

3. EXPERIMENTAL WORK

3.1. Overview

It has been shown in previous research work that fly ash based heat cured geopolymer concrete exhibited excellent durability properties. However, heat curing requires a controlled curing environment to produce the desired mechanical and durability properties. Therefore, this experimental study was carried out on GGBFS blended fly ash based geopolymer concrete cured at ambient temperature. The main objective is to explore durability related properties of geopolymer concrete cured at ambient temperature. Durability related tests were conducted on the specimens cast in the laboratory as per standard practices. Concrete mixtures were selected after number of trial mix designs and testing for the required strengths. Ten geopolymer concrete mixes were used to cast the test specimens. Two OPC concrete mixtures also designed as per ACI 211.1-91 and used to cast the OPC concrete specimens. Commercially available materials were used in the concrete mixes.

3.2. Experimental programme

For this study, low calcium 'Class F' fly ash locally available in Western Australia was used. Other ingredients used in this study included local coarse and fine aggregates, ground granulated blast furnace slag, alkaline solutions and water. Properties of the aggregate were tested in accordance with the standard guidelines outlined in Table 3-1. Ten geopolymer concrete mixtures were prepared in laboratory to investigate the properties of hardened geopolymer concrete. Two mixtures with ordinary Portland cement were also used to compare with the results of geopolymer concrete mixtures. The concrete samples were prepared to determine the mechanical and durability properties of concrete. A complete list of the tests is given in Table 3-2.

Table 3-1: Properties of aggregates tested.

Aggregate Properties	Standard followed
Sieve analysis/Fineness Modulus	AS 1289.3.6.1-2009 (Standard Australia,1996c)
Relative density/Specific gravity	ASTM C127-07 and ASTM C128-97 (ASTM standard 1997)
Absorption	
Bulk density/ Unit weight	ASTM C29/C29M-09 (ASTM standard 2009)

Table 3-2: Tests to assess the characteristic of the concrete mixtures

Properties	Tests	Standard followed
Mechanical	compressive strength	AS 1012.9-1999 (Standard Australia,1999c)
	Indirect tensile strength	AS 1012.10-2000 (Standard Australia,2000)
	Flexural strength	AS 1012.11-2000 (Standard Australia,2000)
Durability	Drying shrinkage	AS 1012.13-1992 (Standard Australia,1992)
	Sulphate resistance	AS 2350.14-2006 (Standard Australia,2006) & ASTM C1012/C1012M-13 (ASTM standard 2013)
	Volume of permeable voids (VPV)	AS 1012.21-1999 (Standard Australia,1999)
	Sorptivity	ASTM C 1585-04 (ASTM standard 2004)
	Alternative wetting and drying	Kasai and Nakamura, 1980; Olivia and Nikraz, 2012

3.3. Descriptions of materials

3.3.1. Fly ash

Low-calcium class F fly ash (ASTM C 618-12) was collected from the commercial supplier and stored in large sealed bags at designated laboratory storage area. Class F fly ash normally produced from burning anthracite or bituminous coal. It usually consists mainly of alumina and silica and has a higher loss on ignition (LOI) than Class C fly ash. The chemical and mineral compositions of the class F fly ash were determined by X-Ray Fluorescence (XRF) analysis and are given in Table 3.3.

Table 3-3: Chemical composition of fly ash and GGBFS

Sample	Fly ash (%)	Class F Fly ash [a] (%)	GGBFS (%)
SiO_2	53.71	-	29.96
Al_2O_3	27.20	-	12.25
Fe_2O_3	11.17	-	0.52
SiO_{2+} Al_2O_{3+} Fe_2O_3	92.08	70.0 min	-
CaO	1.90	10.0 max	45.45
Na_2O	0.36	-	0.31
K_2O	0.54	-	0.38
SO_3	0.30	5.0 max	3.62
P_2O_5	0.71	-	0.04
TiO_2	1.62	-	0.46
LOI[b]	0.68	6.0 max	2.39

[a] ASTM C 618, [b] Loss on ignition

3.3.2. GGBFS

Ground granulated blast-furnace slag (GGBFS) is a glassy granular material. It is a non-metallic product, consisting of silicates and aluminosilicate of calcium and other bases. The GGBFS used in this study was purchased from a commercial supplier. The chemical and mineral compositions of GGBFS are given in Table 3.3. The properties of this GGBFS conformed to the Australian Standard, AS 3582.2-2001 (Standards Australia, 2001).

3.3.3. Ordinary Portland cement

Ordinary Portland Cement (OPC) conforming to AS3972 (Standards Australia, 2010) was used in this study. The main chemical components of ordinary Portland cement are Calcium, Silica, Alumina and Iron. Calcium is usually derived from limestone, marl or chalk, while silica, alumina and iron come from the sands, clays & iron ores. Typical properties of the OPC used are given in Table 3-4. Ordinary Portland cement was stored in unopened bags and was stacked in the laboratory on a platform above floor to prevent the ingress of moisture.

Table 3-4: General specifications of swan general Portland cement-type GP (Swan cement 2012).

Chemical properties

Parameter	Test Method	Typical value	Range	specification as per AS3972-2010
SiO_2 (%)	XRF	21.1	20.4-21.8	-
Al_2O_3 (%)	XRF	4.7	4.3-5.1	-
Fe_2O_3 (%)	XRF	2.7	2.5-2.9	-
CaO (%)	XRF	63.6	62.6-64.6	-
MgO (%)	XRF	2.6	2.4-2.8	-
SO_3 (%)	XRF	2.5	2.2-2.8	3.5% max
LOI[a]	AS2350.2	2	1.0-3.0	-
Chloride	ASTMC114-11	0.01	0.01-0.03	-
Na_2O equivalent	ASTMC114-11	0.5	0.40-0.60	-

Physical properties

Parameter	Test Method	Typical value	Range	specification as per AS3972-2010
Fineness index (m^2/kg)	AS2350.8	400	370-430	-
Normal consistency (%)	AS2350.3	28.5	27.5-29.5	-
Soundness (mm)	AS2350.5	1	0-2	5 mm max
Initial setting Time (min)	AS2350.4	120	90-150	45 mins minimum
Final setting Time (min)	AS2350.4	195	165-225	10 hrs max
Compressive strength (MPa)	3 days	38	35-42	-
	7 days	47	44-51	25 MPa min
	28 days	60	56-64	40 MPa min

3.3.4. Coarse aggregates

Coarse aggregates with nominal maximum sizes 7mm, 10mm and 20mm of crashed granite were used in this study. The grading plays a significant role in influencing concrete properties, including drying shrinkage and workability of concrete (Lai, 1999). Therefore, a suitable grading of aggregates was determined in accordance with the AS 2758.1 -1998 (Standard Australia, 1998). Apart from the aggregate grading, surface texture of aggregate also play an important role in developing the bond between an aggregate particle and a cementing material. A rough surface texture gives the cementing material something to grip, producing a

stronger bond, and thus creating stronger concrete. The surface texture of the aggregate used in this study was granular which was also complied with the AS 2758.1 Table B5. In this study, a combination of different sizes of aggregate was used. The final combined aggregate volume was a combination of 41% 20mm, 9% 10mm aggregate and 15% 7mm aggregate and 35 % sand. All three types of coarse aggregates were combined with sand to obtain a dense graded aggregate combination. The fineness modulus of combined aggregates was 6.12.

Water Absorption of aggregates is also another key performance indicator for concrete mixtures. Higher absorption rates pose potential problems for concrete production given that water demand and workability can be severely altered. Thus, the absorption values for coarse and fine aggregates were measured for every different size of the aggregates. The absorption values were below the acceptable value 2% according to the AS 2758.1 section 3.7.2 (Standard Australia, 1998).

3.3.5. Fine aggregates

The fine aggregate used in this study was locally available clean natural sand with rounded or sub-rounded particles. The fine aggregate was obtained from a local supplier and the same fine aggregate was used for all the batches. The grain size distribution curve for the fine aggregate was performed according to AS2758.1-1998 (Standard Australia, 1998). The aggregates were prepared to saturated surface dry (SSD) condition. The fine aggregate had an average fineness modulus of 2.67 and the absorption value of fine aggregate was 0.99% which was within the acceptable limit of 2% as per AS 2758.1-1998 (Standard Australia, 1998).

3.3.6. Alkaline liquid

The alkaline activation of fly ash in this study was conducted by a combination of 14M NaOH and sodium silicate solutions. The sodium silicate solution was obtained from from coogee chemical, Australia. The NaOH used in this study was in pellets from with 97-98% purity and were dissolved in water at least 6 hours

prior to mixing. The properties and composition of the sodium silicate solution (Na_2SiO_3) supplied by the producer are shown in Table 3.5.

Table 3-5: Chemical composition of sodium silicate.

Grade	NA46
% NaOH (w/w)	14.7
% Na_2O (w/w)	11.4
% Si_2O (w/w)	30.1
Wt. ratio SiO_2/Na_2O	2.65
Specific gravity (gm./ml @ 20^o C)	1.458
Appearance	Viscous clear to light yellow liquid
P^H	12.8
Solubility (water)	Soluble
% volatiles	> 60% (water)

3.3.7. Water

Impurities in mixing water, when excessive, may affect not only setting time, concrete strength, and volume stability (length change), but may also cause efflorescence or corrosion of reinforcement (ACI 318 section 3.4). The potable tap water used in the mixtures was taken from the Curtin university concrete laboratory which is originally supplied by water distributing authority of Perth, Australia.

3.3.8. Super plasticiser

Naphthalene-based Superplasticizer has been used in the concrete mixtures in constant dosage of 1.25 % of the binder weight. This type of admixture was mainly used to achieve a desirable slump. The admixture was supplied by BASF chemicals commonly known as ‘Rheobuild 1000’. It had a specific gravity of 1.2 and a solid content of 40%. The superplasticizer complies with ASTM C494-12 (ASTM standard, 2012a) as Class A and F admixture.

3.4. Concrete mix design

3.4.1. Geopolymer concrete mix design

The selection of the concrete mixture proportions involves a balance between economy and requirements for workability, strength, durability, density, and appearance. The numbers of parameters considered during the study were aggregate content, alkaline activator solution, sodium silicate to NaOH ratio, molarity of NaOH solution and the method of curing. The parameters were chosen based on the previous research. An alkaline solution to binder ratio in the range of 0.35–0.40 was shown to give good strength and microstructure of the geopolymer concrete (Palomo et al., 1999). Sodium silicate to sodium hydroxide ratios of 1.5–2.5 was shown to be appropriate (Hardjito et al., 2004). The geopolymer concrete was wet-mixed for at least 3-4 minutes and all the concrete samples were ambient-cured (15-20^{o}C) after casting until tested. The following steps were followed in the design of geopolymer concrete mixtures:

Step 1: Select alkaline activator content in the mixtures

Workability of geopolymer concrete is controlled by the mass ratio of the alkaline liquid to binder. Based on the laboratory trial mix results, two different series of geopolymer concrete: one with the 40% alkaline activator (Series A) and the other with 35% alkaline activator (Series B) was chosen.

Step 2: Calculate the content of binder materials.

In GGBFS blended fly ash based geopolymer concrete, the fly ash was replaced by GGBFS at 0%, 10% or 20%. In order to determine the required quantity of different ingredients in geopolymer mixtures, a constant amount of binder was assumed. In this study, the total binder content of the geopolymer mixtures was kept at 400 Kg/m^3, for both the series. There was 360 kg / m^3 of fly ash and 40 kg / m^3 of GGBFS in the mixtures with 10% GGBFS.

Step 3: Select the maximum size of aggregate

ACI 318 section 3.3.2 states the nominal maximum size of coarse aggregate should not exceed than (a) 1/5 the narrowest dimension between sides of forms, (b) 1/3 the depth of slabs, nor (c) 3/4 the minimum clear spacing between individual reinforcing bars or wires, bundles of bars, or prestressing tendons or ducts. The combined aggregates may be selected to match the standard grading curves used in the design of Portland cement concrete mixtures. Based on the previous studies, a maximum size of coarse aggregate of 20 mm was used in this study. A combination of 20 mm, 10 mm and 7 mm nominal size aggregate were used in all mixtures.

Step 4: Select optimum coarse aggregate content

The optimum content of coarse aggregates depends on its strength, potential characteristics and maximum size. Moreover, the nominal maximum size and grading also play vital roles to achieve the desirable workability for geopolymer concrete. The unit-weight of concrete was assumed as 2400 kg/m^3 in calculation of the mass of normal density aggregates in SSD condition. The mass of binder material was kept constant as 400 kg/m^3 throughout the study.

Mass of the binder= 400 kg/m^3

For series A with 40% alkaline activator content

Mass of alkaline activator content= 0.4*400= 160 kg/m^3

Mass of aggregate =2400-400-160= 1840 kg/m^3

A combination of 41% of 20mm, 9% of 10mm , 15% of 7 mm nominal size of coarse aggregate and 35% of sand was used in this study for all Series A mixtures.

Mass of 20mm aggregate= 0.41*1840= 754.4 kg/m^3

Mass of 10mm aggregate= 0.09*1840= 165.6 kg/m^3

Mass of 7mm aggregate= 0.15*1840= 276 kg/m^3

Mass of Sand = 0.35*1840= 644 kg/m^3

Step 5: estimate the alkaline liquid content

Mass of alkaline liquid for series A was taken as 40% of the binder.

Mass of alkaline liquid content= 0.4*400 = 160 kg/m^3

For series A, the sodium silicate solution-to-sodium hydroxide ratio varied from 2.5 to 1.5

For SS/SH ratio 2.5

Mass of sodium hydroxide solution = 160/ (1+2.5) = 45.7 kg/m^3

Mass of sodium silicate solution = 160-45.7= 114.3 kg/m^3

For SS/SH ratio 1.5

Mass of sodium hydroxide solution = 160/ (1+1.5) = 64 kg/m^3

Mass of sodium silicate solution = 160-64= 96 kg/m^3

The same procedure was followed in calculation of aggregates, binder, sodium hydroxide and sodium silicate contents of the mixtures of series B. The workability of fresh geopolymer concrete for series B was relatively low due to lower liquid content than A. To improve the workability of Series B , commercially available super plasticizer of about 1.5% of mass of binder, i.e. 400 x (1.5/100) = 6 kg/m^3 and a constant dosage of 8 kg/m^3 water was added to the mixture to facilitate ease of placement of fresh concrete.

3.4.2. Ordinary Portland cement concrete mix design

The mix design for ordinary Portland cement concrete was based on the method recommended by the ACI committee 211 (2009),. The mix design was done in the steps described below. The design calculations for OPC concrete are given in Appendix A.

- The required (target) average compressive strength (f'_{cr}) at 28 days for mix design was determined by adding up an empirical factor (k) to the design compressive strength (f'_c) as per equation 3-1:

$$f'_{cr} = f'_c + k \qquad (3\text{-}1)$$

- The W/C ratio was selected based on the target strength and non-air entrained concrete.

- Air content, as percentage of the concrete volume, was estimated based on no air- entrained type of concrete and exposure conditions, and nominal maximum size of aggregate.
- Slump, as a measure of workability, was selected depending upon the type of structure.
- Water content, was determined based on the type of concrete (non-air entrained), and specified slump. Then it was adjusted for the types of aggregates.
- Cement content was calculated based on the w/c ratio and the water content.
- Coarse aggregates content of concrete was determined based on the nominal maximum size of aggregate and the fineness modulus of sand.
- Once the water content, cement content, and the coarse aggregate content of concrete was determined, the fine aggregate was then calculated by subtracting the weight of the known ingredients from unit weight of the fresh concrete.
- Finally, water content was adjusted based on the absorption and the current moisture content of the coarse and fine aggregates, in account of saturated surface dry condition of the aggregates.

3.4.3. Mixture proportions

Two series of geopolymer concrete mixtures named as series A and series B were proportioned in this study. The mix design described in previous section was followed. In series A, four geopolymer mixtures were prepared by varying the ratio of SS/SH and the GGBFS quantity. The quantity of alkaline activator and the aggregate content were kept constant for all mixtures in series A. In series B, six geopolymer mixtures were studied by reducing the alkaline activator content from 40% to 35 %. The ratio of SS/SH and the GGBFS content also varied in the same way as in series A. Superplasticiser and the water were added according to the mix design data outlined in section 3.4.1. Two ordinary Portland cement concrete mixtures were also designed as per the procedure outlined in ACI 211.1-91 (ACI committee 211, 2009). The proportioning of ingredients was conducted based on

the weight method. The mixture proportions of geopolymer concrete are given in Table 3 -6.

Table 3-6: Mixtures proportions of the concrete mixtures.

Mixtures	A				B							
	GPC1	**GPC2**	**GPC3**	**GPC4**	**GPC5**	**GPC6**	**GPC7**	**GPC8**	**GPC9**	**GPC10**	**OPC1**	**OPC2**
Label	A40 S10 R2.5	A40 S20 R2.5	A40 S10 R1.5	A40 S20 R1.5	A35 S00 R2.5	A35 S10 R2.5	A35 S20 R2.5	A35 S00 R1.5	A35 S10 R1.5	A35 S20 R1.5	-	-
CA[a]	1209	1209	1209	1209	1222	1216	1216	1222	1216	1216	1054	1054
Sand	651	651	651	651	658	655	655	658	655	655	768	740
Fly ash	360	320	360	320	400	360	320	400	360	320	-	-
GGBFS	40	80	40	80	0	40	80	0	40	80	-	-
Cement	-	-	-	-	-	-	-	-	-	-	446	366.4
SH[b]	45.7	45.7	64	64	40	40	40	56	56	56	-	-
SS[c]	114.3	114.3	96	96	100	100	100	84	84	84	-	-
Water	-	-	-	-	-	8	8	-	8	8	165	201.6
SP[d]	-	-	-	-	6	6	6	6	6	6	-	-

[a]Coarse aggregate, [b]Sodium hydroxide, [c]Sodium silicate, [d]Superplasticiser

3.5. Manufacture of test specimens

3.5.1. Preparation of aggregate

Both the coarse and fine aggregate were prepared to saturated surface dry (SSD) condition. The preparation of aggregate to SSD condition was achieved by soaking the aggregate in water for 24 hours and let it dry in the air until the SSD condition was reached. The aggregates were stored in sealed containers when they reached to SSD condition. In geopolymer concrete, it was necessary to prepare aggregates to SSD condition in order to avoid absorption of the alkaline solution by the aggregates thus affecting the polymerization of the fly ash. Conversely, batching of concrete based on inaccurate aggregate moisture contents can impact workability, strength development, air entrainment, permeability, and shrinkage of the geopolymer concrete mixture. The actual moisture content of aggregates was tested before each batching of the geopolymer mixture. For this, approximately 1 kg of aggregate was placed in a pan. Then the pan was stored in the oven at 105^0C

for a period 24 hours. After 24 hours, the pan was removed from the oven and the weight of the pan was deducted to get the weight of oven dried (OD) aggregate. The difference in weight represents the total moisture content of the aggregate. Similar procedure of coarse aggregate was applied for the fine aggregate to check moisture content prior to mixing.

Figure 3-1: Preparation of coarse aggregates to SSD condition

3.5.2. Preparation of alkaline liquid.

The alkaline activator was a combination of sodium silicate and sodium hydroxide solutions. Sodium hydroxide solution of 14M concentration was prepared by mixing 97-98% pure pallets with tap water. The sodium silicate was added to enhance the formation of geopolymer precursors or the polymerization process (Xu et al., 2000). The mass of NaOH solids was measured as 14×40 = 560 grams per litre of NaOH solution of 14M concentration. Mixing of the NaOH was done in a fume cabinet of the designated laboratory area. Sodium silicate solution with SiO_2 to Na_2O ratio by mass of 2.61 (SiO_2=30.0%, Na_2O= 11.5% and water=58.5%) was used in this study. The alkaline activator was prepared in the

laboratory by mixing sodium silicate and sodium hydroxide solutions at the required ratio about 1 hour before actual concrete mixing.

3.5.3. Mould for casting test specimens.

Moulds were prepared for casting the concrete samples. Cylindrical specimens (100 × 200 mm) were cast for the compressive strength, sulphate attack, VPV, sorptivity, alternate wetting & drying tests. Specimens of 150 × 200 mm cylinders, 100 × 100 × 400mm beam and 75 × 75 × 285mm prisms were cast for the split tensile strength, modulus of rupture and drying shrinkage tests, respectively.

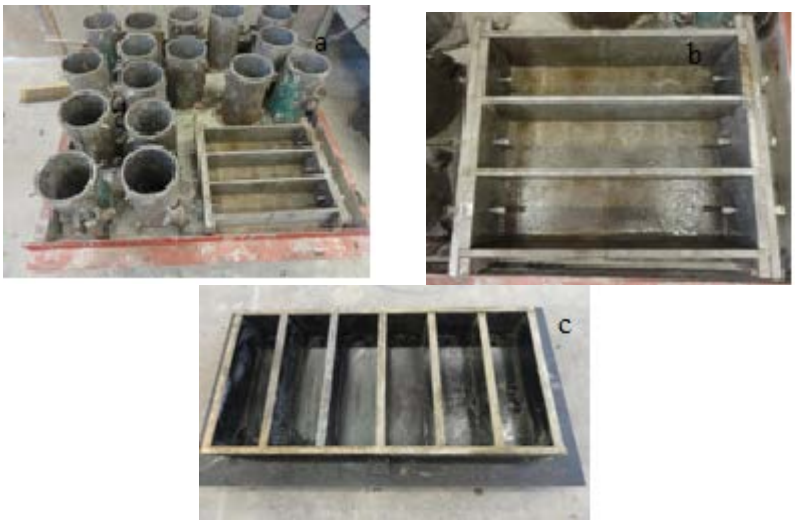


Figure 3-2: Different types of moulds: (a) compressive strength moulds (b) drying shrinkage mould (c) flexural strength mould

Every mould was properly cleaned and tightened to maintain exact dimension during casting. The inner surface of the mould was coated with a concrete releasing agent to facilitate demoulding process after hardening of concrete.

3.5.4. Manufacture of fresh concrete and casting.

The mixing for all geopolymer and OPC concrete was undertaken using a 70-litres mixer shown in Figure 3.3. The concrete mixing was done according to the mixing procedure outlined in AS 1012.2 (Standard Australia, 1994). Due to the limitation of mixer pan capacity each concrete mixture was prepared in two

batches named as Batch-1 and Batch-2. The mixing pan was cleaned to remove any type of foreign material before each mixing. The coarse aggregates which were prepared in saturated-surface-dry (SSD) condition firstly loaded in the mixing pan followed by sand. Then the fly ash was loaded followed by GGBFS for the geopolymer concrete mixtures. All dry materials in the pan mixer were mixed for about three minutes. Geopolymer mixtures with 35% alkaline activator content were relatively sticky and less workable than the mixture having with 40% activator content.

Figure 3-3: Alkaline activator is being added in the geopolymer concrete mixture.

Figure 3-4: Freshly mixed concrete placed in cylinders.

To improve the workability of geopolymer mixtures having with 35% alkaline activator content, water and superplasticizer was added. The mixing technique for geopolymer concrete was as follows:

- For 40 % alkaline activator: after mixing the dry materials for 3-4 minutes alkaline liquid was added and mixed for another 2 minutes.
- For 35 % alkaline activator: firstly alkaline liquid was added into the mixtures. Then water along with the super plasticizer was added slowly while the mixing in progress. The mixing was continued until all the materials were thoroughly mixed.

It was found that the fresh GGBFS blended fly ash-based geopolymer concrete was dark in colour and cohesive in nature. The amount of extra water added in the mixture played an important role on the behaviour of fresh concrete which was usually followed by low compressive strength result of hardened concrete. After mixing the fresh concrete, slump test was done in accordance with ASTM C 143 (ASTM Standard, 2010). The test specimens were then cast immediately. Prior to use, cylinder and other moulds were visually inspected for defects such as rounding of edges and any cracks. The moulds were oiled with VALSOF PE-40 for geopolymer concrete and greased for OPC concrete at least 30 minutes prior to filling with concrete. After pouring each layer, the moulds were compacted on a vibration table. The vibration was stopped when there was a very few bubbles liberating and aggregates were just dipped in the mortar.

3.5.5. Demoulding, curing and capping.

The concrete specimens were stripped on the day after casting at approximately 24±8 hours and marked with respect to batch and mix id no, then immediately returned to the curing room. During the stripping time extra care was taken to avoid any type of damage of the specimens. The geopolymer and OPC concrete samples were put in different curing environment conditions.

Figure 3-5: Geopolymer concrete specimens cured at ambient condition.

- Geopolymer concrete samples were cured at ambient condition (15-20^{0}C and 60±10% RH) until the test days in the designated laboratory curing room.
- Ordinary Portland cement concrete specimens were cured under water up to 28 days and after that they were cured in the room environment (23^{0}C and 60±10% RH) until test.

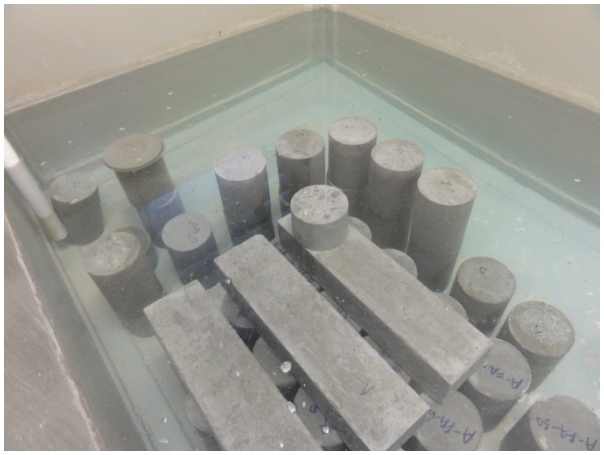


Figure 3-6: OPC concrete specimens cured in lime saturated water curing tank.

Capping was done at 26 days in accordance with ASTM C-617 (ASTM standard, 2012b). Forney Hi-cap high strength capping compound was used for capping of

the cylinders. If any defects were found in capping then cylinder was recapped before the testing.

3.6. Test procedure

3.6.1. Particle size distribution.

Sieve analysis was used to determine the proportion of particles of different sizes within a particular aggregate product. The test used a tower of interlocking sieves with apertures that decreased in size from top to bottom. Sieve analysis was conducted as per the AS 1289.3.6.1-2009 (Standard Australia, 2009).

Fine aggregate

- The test sample (1kg) was dried to a constant weight at a temperature of 110 ± 5^{o}C and weighed.
- For sieve analysis, 500gm of oven dried fine aggregate was taken. The sand sample was separated in two parts as the mass of the tested sample was exceeding than the recommended value outlined in AS 1289.3.6.1 (Each part not less than 150gm). At the end of the test the retained weight of particles on each sieve was recombined and considered these as single sieve functions.
- The sample was than sieved by using a mechanical shaker. A set of sieves (2.36mm, 1.18mm, 600µm, 300µm and 150 µm) were used.
- On completion of sieving, the material on each sieve was weighed and cumulative weight passing through each sieve was calculated as a percentage of the total sample weight.
- Finally, the fineness modulus was obtained by adding cumulative percentage of aggregates retained on each sieve and dividing the sum by 100.

Coarse aggregate

Similar procedure as in the fine aggregate was applied for sieve analysis of the coarse aggregate. The procedure is follows

- The sample was dried at a temperature of 110 ± 5^{o}C to a constant mass in accordance with the AS 1289.3.6.1 (Standard Australia, 2009) and the value was recorded to the nearest 0.1 percent of the total sample mass or 0.1 gm.
- The sieve used for coarse aggregate sieving were 26.5mm, 19mm, 9.5mm, 4.75mm, 2.36mm and 1.18mm. The Sieves were placed in the mechanical shaker and shaking for approximately 10 minutes.
- Finally the mass of the retained aggregate were recorded.

3.6.2. Water absorption and relative density.

Coarse aggregate

Relative density and water absorption of the coarse aggregates was determined according to ASTM C 127-07 (ASTM standard, 2007). The amount of each type of coarse aggregate was calculated based on the standard requirement such as 3kg of 20mm, 2kg of 10mm and 7mm. Firstly, the coarse aggregates were kept immersed in water for 24± 4 hours. After that, the test samples were removed from water and rolled it in a large absorbent cloth until all visible films of water were removed. The larger particles were wiped out individually and then the mass of the test sample was determined in the saturated surface-dry condition. After taking the SSD weight, the weight of samples in water was recoded. Finally, the samples were dried in the oven at 110 ± 5^{o}C to a constant mass. The weight of the samples was taken after cooling to a comfortable temperature. Absorption and relative density of the coarse aggregates were calculated by the equations 3-2 and 3-3 respectively.

Absorption, % = ((B - A)/A) ×100---------- (3-2)

Relative density (Specific gravity) (OD) = A / (B – C) ---------- (3-3)

Where,

A = mass of oven-dry test sample in air, gm.

B = mass of saturated-surface-dry test sample in air, gm. and

C = apparent mass of saturated test sample in water, gm.

Fine aggregate

Relative density and water absorption of the fine aggregate was determined in accordance with ASTM C 128-12 (ASTM standard, 2012). The method was based on the ability of the material to slump in a cone (90±3mm dia at bottom and 40±3mm dia at top). This method required a 24 hour saturation period for the fine aggregate (approximately 1 kg). After full saturation, the material was progressively dried and checked in a small cone. The cone was removed and the slight slumping of the molded fine aggregate indicated that it has reached a saturated surface-dry conditions. When the sample reached to SSD condition, half of the sample was put in the oven at 110 ± 5^0C to measure the water absorption of the fine aggregate. The rest of the sample was used to determine the relative density of the fine aggregate by gravimetric (pycnometer) method.

The SSD sand placed into the pycnometer and filled with water to 90% of the pycnometer's capacity. The pycnometer then rolled, inverted and agitated manually to eliminate air bubbles. This procedure was repeated several times to ensure that any entrapped air was eliminated. Additional water was added to the pycnometer in its calibrated capacity at room temperature and the mass was recorded. Finally, mass of the empty pycnometer and the mass of the pycnometer filled to its calibrated capacity with water at room temperature were taken.

Absorption, % = ((S- A)/A) ×100 ---------- (3-4)

Relative density (specific gravity) (OD) = A/ (B+S – C) ---------- (3-5)

Relative density (specific gravity) (SSD) = S/ (B+S – C) ---------- (3-6)

Where,

A = mass of oven-dry test sample in air, gm.

S= mass of saturated surface dry sample, gm,

B = mass of pycnometer filled with water, gm, and

C = mass of pycnometer filled with specimen and water, gm.

Figure 3-7: Fresh geopolymer concrete and slump measurement.

3.6.3. Workability test.

The term workability is broadly defined; no single test method is capable of measuring all aspects of workability. According to ACI 116R-00 the workability can be defined as "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." The strength and durability of hardened concrete depend on concrete having appropriate workability. Workability encompasses many interrelated terms, such as flow ability, consistency, mobility, pump ability, plasticity, compatibility, stability, and finish ability. Thus, it is essential to consider workability in the mix design to ensure ease of placement and durability of concrete. Testing for workability of fresh concrete was done in accordance with ASTM C 143 (ASTM Standard, 2010). A mould with the dimensions of 300mm in height, 100mm diameter at the top and 200mm diameter at the bottom is used to measure the slump of the fresh concrete. The following steps were followed during the testing:

- Initially the internal surface of the mould and base plate was cleaned and wiped out with a damp cloth.
- Then, the mould was fixed firmly over the base plate and held firmly in place by standing on the foot pieces.
- The mould was filled in three equal layers and each layer was compacted with 25 strokes. A temping rod having 600 mm length and 15mm diameter

was used for compaction. Each layer was compacted in such a way that the rod can penetrate at least 25 mm of the previous layer.

- After rodded and levelled the top layer, excess material was removed from the base of the mould. Then the mould was lifted vertically in about 3 ±1 seconds without any lateral of torsional displacements.
- Finally the deference between the height of the mould and the edges of the top surface of the concrete was measured. The average of these measurements is reported as the slump value.

3.6.4. Compressive strength test

Compressive strength determination was carried out on cylindrical specimens of 100 mm diameter and 200 mm height according to AS1012.9-1999 (Standard Australia, 1999). All the samples for geopolymer concrete were kept in ambient curing (15-20^{o}C) conditions until tested. The specimens of OPC concrete samples were continuously cured in saturated lime water until 28 days after the casting. Finally, compressive strength testing was carried out by the controls MCC8 machine on three specimens at each age and the average value to the nearest 0.5 MPa has been reported. The procedure used to test the specimens is as follows:

- Sulphur capping in accordance with ASTM C 617-12 (ASTM Standard international, 2012b) was used to provide a uniform load distribution.
- The cylinder diameter and height were measured in two locations at right angles to each other at mid height of the specimen and average value was taken to calculate the cross sectional area.
- The cylinder was placed in the centred of the lower plate of compression testing machine and loaded with a constant rate of 0.333 MPa/sec (equivalent to 20±2MPa compressive stress per minute) until failure.
- The test age, any types of defects in the specimens, identifications of specimens, cylinder diameter and height, maximum applied load and compressive strength were recoded after each testing.

Figure 3-8: Compressive strength with sample under loading.

The compressive strength of the specimens was calculated using the equation (3-7)

$$f_c = \frac{1000 \times P}{A} \quad (3\text{-}7)$$

Where,

f_c= Compressive strength (MPa)

P= maximum force applied (kN),

A=Cross sectional area (mm^2)

3.6.5. Indirect tensile strength test

The splitting tensile strength of the concrete specimens was experimentally measured according to AS 1012.10-2000 (Standard Australia, 2000). To obtain the splitting tensile strength, a cylinder of dimension 150×300 mm (diameter × height) was subjected to compressive loading along its length and were tested at the age of 7days, 28days and 90days using the control MCC8 machine. The test involved the following steps:

- The diameter & the length of the test specimen were measured by averaging the three consecutive values.
- The specimen was placed in the test rig with 15-25 mm wide strips of cardboard. The assembly was positioned to ensure that the centre lines of

the specimens were vertical and was loaded centrally on its longitudinal axis at the both side of the test plan.

- Finally, load was applied to the specimens through the MCC8 machine without any shock and increased continuously with a constant rate of 1.5 ± 0.15 MPa/min. The test was terminated at the failure load and the failure load was recorded to calculate the maximum tensile stress.

Figure 3-9: Indirect tensile strength test in progress.

Two samples were tested at each age and the average strength was reported. The splitting tensile strength of the specimens was calculated using the equations (3-8).

$$f_{ct} = \frac{2000P}{\pi LD} \text{ ---------- (3-8)}$$

Where,

f_{ct} = Indirect tensile Strength (MPa),

P = Maximum applied force (kN),

L= Length of the specimens (mm),

D= Diameter of the Specimens (mm)

3.6.6. Flexural tensile strength test

The flexural strength is expressed as modulus of rupture in MPa and obtained in accordance with AS 1012.11-2000 (Standard Australia, 2000). Flexural strength

Figure 3-10: Flexural strength test in progress.

of the specimens for each mix was measured by loading 100mm× 100mm concrete beam with a span length of 400mm and tested for two specimens at 7, 28 and 90 days. The test involved the following steps:

- The surface of the specimen was cleaned for any oil and grit to facilitate a uniform loading.
- The specimen was placed over the two bottom rollers (set a 300mm apart) and then the loading roller was brought into contact of the top surface of the specimen.
- Load was applied to the sample without any shock and increased continuously at a rate equivalent to 0.0167 MPa/sec. The maximum applied force, the average width and average depth at failure section were recoded.

  The modulus of rupture was determined by applying the equation (3-9)

$$f_{cf} = \frac{1000 \times \mathrm{PL}}{\mathrm{B}D^2} \quad \text{----------} \quad (3\text{-}9)$$

Where,

f_{cf} = modulus of rupture (MPa),

P = maximum applied force indicated by the testing machine (kN),

L = span length (mm),

B = average width of the specimen at the section of failure (mm),

D = average depth of specimen at the section of failure (mm),

3.6.7. Drying shrinkage.

Drying shrinkage is the reduction of a hardened concrete mixture due to the loss of capillary water. It causes an increase in tensile stress, which may lead to cracking, internal warping, and external deflection, before the concrete is subjected to any kind of loading. Cracking due to drying shrinkage is a common form of crack in concrete. Therefore, reducing drying shrinkage will reduce the associated cracking and reduce the risk of having large member in the concrete structure.

The determination of drying shrinkage was experimentally carried out in the laboratory. The method of AS 1012.13 -1992 (Standard Australia, 1992) was followed to measure the drying shrinkage throughout the study. Specimens for drying shrinkage test were 75×75×285 mm prisms with the gauge studs as shown in Figure 3-11. The following steps were followed in the test:

- Three specimens were prepared for each type of mixture. The shrinkage strain measurements started on the seventh day after casting the specimens. On the seventh day after casting, the specimens were demoulded and the first measurement was taken.

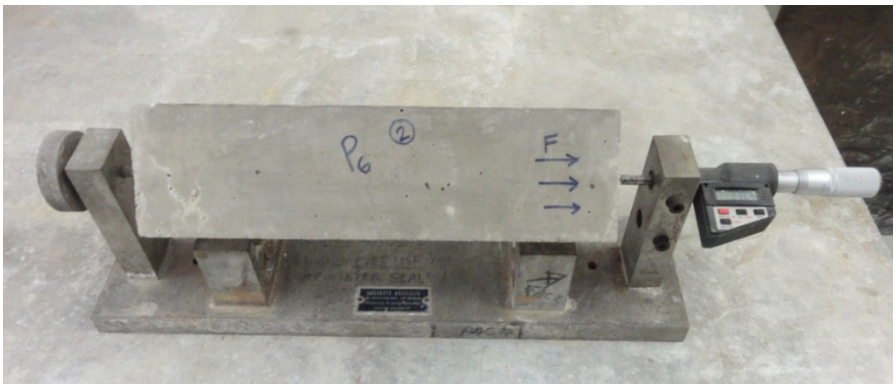


Figure 3-11: Length of drying shrinkage specimen being measured by a horizontal length comparator.

- During the measurement the test specimens was firstly, placed in the comparator so that its axis was aligned with the measuring anvil. The

length difference was recorded from the micrometer when the anvils were in contact with the specimen. After taking the value, the specimen was removed from the comparator and replaced again in the same orientation. The process was repeated at least five times and the value was recorded.

- After taking the values the specimens were then placed in the laboratory curing room rack so that there was a clearance of at least 50 mm on all sides.
- The change in length was measured at 7, 14, 21, 28, 56, 90, 120 and 180days.
- Three measurements were taken for each specimen and the average value was recorded. Finally, the length change was found using the equation 3-10

$$L_{ds} = (L_t - L_i) \times 10^6 / L \quad \text{---------- (3-10)}$$

Where,

L_{ds} = Drying shrinkage in microstrain.

L_t = Length of the individual specimen at any specified time t (mm)

L_i = initial length of the individual specimen (mm)

L= Gauge length (250mm)

3.6.8. Sulphate resistance test

Cylinder specimens of dimension 100 mm diameter and 200 mm height were cast for compressive strength and change in mass tests, and prism specimens of 75 mm ×75 mm ×285 mm were cast to test the length change for each mixture. Two specimens were used for compressive strength and two for change in mass test, while three specimens were used for change in length test. The samples were immersed in 5% sodium sulphate solution at the age of 7 days for the length change test and at the age of 28 days for compressive strength and mass change tests. The specimens were kept immersed for up to 180 days in a room at 23 ^{0}C. The volume proportion of sulphate solution to specimens was maintained in ratio

of four to one. The sulphate solution was replaced with fresh solution at each month to maintain the concentration of the solution.

3.6.8.1. Change in mass

Change in mass after immersion in sulphate solution was monitored at 56, 90, 120 and 180 days after the immersion. The geopolymer concrete samples were ambient cured until the age of 28 days and then immersed in the 5% sodium sulphate. After, the selected exposure period, the samples were removed from the sulphate solution and wiped clean prior to the measurement. Mass of the specimen was taken by a laboratory scale and was returned to the sulphate solution container immediately after the measurement was done. The reported loss was the average value for two samples.

Figure 3-12 Specimens immersed in sodium sulphate solution

3.6.8.2. Change in compressive strength

To determine the change in compressive strength of geopolymer and OPC concrete, the compressive strength for selected samples were tested at the age of 56, 90 and 180 days in accordance with the AS1012.9-1999 (Standard Australia, 1999). The samples were removed from the sulphate solution after selected periods of exposure and left for 24 hour for drying. Sulphur capping was used to provide a uniform load distribution and the specimens were tested with a constant rate of 0.333 MPa/sec (equivalent to 20±2 MPa compressive stress per minute) until failure.

3.6.8.3. Change in length

The sulphate expansion test was conducted for 75×75×285 mm prisms in accordance with the AS 1012.13-1992 Standard. Three specimens were made for each mixture and the change in length was measured at 7, 14, 21, 28, 56, 90, 120 and 180 days. During the testing, the specimens were removed from the sulphate solution and wiped out with towels. Then, the change in length was measured by the horizontal length comparator and the samples were returned to the sulphate solution immediately after taking the measurement.

3.6.9. Volume of permeable voids (VPV) test

VPV (Volume of Permeable Voids) of concretes was determined in accordance with the Australian Standard AS1012.21-1999 (Standard Australia, 1999). To obtain the VPV of geopolymer and OPC concrete at 28 and 180 days, a cylinder of dimension 100×200 mm (diameter × height) was cut into four equal slices of approximately 45 mm thickness by using the water cooled diamond saw cutter. The following steps were followed in the test:

Immersed absorption (A_i)

- Firstly, the specimen was put in the oven for 24 hours at a temperature of 105 °C. After 24 hours, each specimen was removed from the oven and put in the desiccator to a temperature of 23 ±2 °C for cooling. The specimen was again put back into the oven for additional 24 hours and continued the drying and cooling procedure until the difference between two successive weights was not greater than 1 gm.
- The oven-dry mass of the cooled specimen was measured and recorded as M_1 to the nearest 0.1 gm.
- After taking the weight of M_1, the specimen was immersed for 48 hours in water at 23 ±2 °C. The samples were surface dried with a towel and weighed to nearest 0.1 gm. The two successive immersion and weighting were continued until the increase of weight not greater than 1gm.
- The weight after immersion was recoded as M_{2i} to the nearest 0.1 gm.

- The immersed absorption (A_i) was calculated by the following equation (3-11).

$$\mathbf{A_i = \frac{(M_{2i} - M_1)}{M_1} \times 100\%} \text{ ---------- (3-11)}$$

Where,

M_1= weight of the oven dried samples (gm)

M_{2i}= Saturated weight after immersion (gm)

Boiled absorption (A_b) and volume of permeable voids (VPV)—

- The surface-dry specimen was placed in the water bath at room temperature and boiled it for a period of 5.5 ±0.5 hours at 100^0C.
- After the boiling period, the specimen was left in water bath for at least 14 hours and the specimen was cooled in the water bath by a natural loss of heat to a final temperature of 23 ± 2 ^{0}C.
- The boiled specimen was made surface-dry by a towel and the weight was recorded as M_{3b} to the nearest 0.1 gm.
- Finally, the sample was suspended in the water bath and the mass of the sample under water M_{4ib} was recoded to the nearest 0.1 gm.

The boiled absorption (M_{3b}) and the volume of permeable voids (VPV) were calculated by the following equations:

$$\mathbf{A_b = \frac{(M_{3b} - M_1)}{M_1} \times 100\%} \text{ ---------- (3-12)}$$

$$\mathbf{VPV = \frac{(M_{3b} - M_1)}{(M_{3b} - M_{4ib})} \times 100\%} \text{ ---------- (3-13)}$$

Where,

M_{3b}= weight of the sample after boiling and cooling (gm)

M_{4ib}= weight of the sample suspended in the water (gm)

3.6.10. Water sorptivity test

Testing for water sorptivity was based on ASTM C1585-2011 (ASTM Standard international, 2011a). The principle of this method is that a concrete specimen has one surface in contact with water while the others are sealed. Thus, water ingress into a non-saturated concrete structure is due to sorption, driven by the capillary

forces. The tests were done at two ages: at 28 days and at 180 days after casting of the specimens. The detailed steps are as follows:

- The specimen used in the testing was consisted of 100 mm diameter and 50 mm thick discs cut (wet). All the samples were cut at 50mm length by ignoring the first 50mm from the top of the cylinder. Three specimens were retrieved from three different cylinders for each mixture.
- After cutting from the cylinder, the specimens were put in the oven for 24 hours at a temperature of 105 °C and checked for constant mass at every 24 hours. The procedure was continued until the difference between two successive weights was not greater than 1gm. The samples were put in the desiccator for 24h to a temperature of 23 ±2°C for cooling.
- The averaged diameter of the test specimen was determined from the four consecutive values.
- The side and top of each specimen's surface was sealed with the epoxy coating material. Weight of the sealed specimens was recorded as initial mass to the nearest 0.01gm.
- Pins were placed at the bottom of the pan to hold the specimens and the pan was filled with the tap water to allow free access of water to the inflow surface. The water level was maintained not more than 3 mm from the bottom face of the specimen during the test.
- Time was recorded immediately after placing the specimens on the support device (initial contact with water).

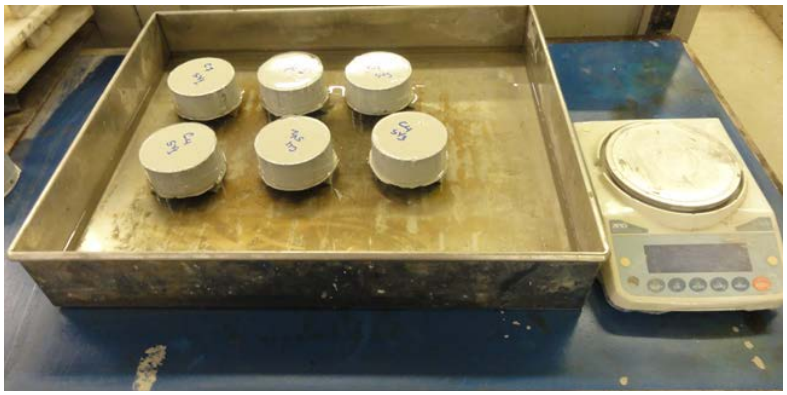


Figure 3-13 Sorptivity test arrangement.

- The quantity of absorbed fluid was measured by weighing the specimen at different intervals. The mass of the specimen was recorded at an interval of 1, 5, 10, 20, 30 minutes and every hour up to 6 hours of initial contact to water. After each time interval the specimen was removed from the pan and wipe out extra water from the surface before taking the weight. After the initial 6 h, the measurements was continued once a day up to 3 days and followed by 3 measurements at 4 to 7 days.
- The absorption, I, which was created by one-dimensional flow of water, is calculated by equation 3-14. Moreover, the initial rate of water absorption ($mm/s^{1/2}$) can be defined as the slope of the line that is the best fit to I plotted against the square root of time ($s^{1/2}$).

$$\mathbf{I} = \frac{\mathbf{M_t}}{\boldsymbol{A \times D}} \quad \text{---------- (3-14)}$$

Where,

I = the absorption (mm),

M_t = the change in specimen mass in grams, at the time t (gm),

A = the exposed area of the specimen, in mm^2, and

D = the density of the water in gm/mm^3.

3.6.11. Alternate wetting and drying test

The effect of alternate wetting and drying cycles on geopolymer and OPC concrete was determine according to the previous study by the Kasai and Nakamura (1980), Olivia and Nikraz (2012). For these experiments, the sample was subjected to immersion in 3.5% NaCl solution for 24 hours followed by drying in different ambient conditions for 24 hours named as 1 cycle. Changes of compressive strength and mass were determined after 28, 45 and 90 cycles for the cylindrical concrete specimens of 100 mm diameter and 200 mm height. All the specimens of geopolymer concrete were ambient cured for 28 days. The volume proportion of NaCl solution to specimens was maintained 3.5 to 1. The NaCl solution was replaced with fresh solution at each month to maintain the

concentration of solution. The drying part of the specimens in the alternate wet-dry cycle was conducted in two different ways in order to study the effect of different drying conditions. The drying condition was either in an oven at elevated temperature or in the air at room temperature. The conditions are described in the following sections.

3.6.11. 1. Drying of specimens in an oven

Cyclic exposure began on the 28 day after casting. Each cycle consisted of 48 hours of which the first half was exposure to wetting, while the other half was exposure to drying in an oven at 80 °C for 24 h. Changes in mass and compressive strength were determined after 28, 45 and 90 cycles of alternate wetting and drying.

Figure 3-14: Specimens soaked in sodium chloride solution and drying in an oven.

3.6.11. 2. Drying in air at room temperature

During wetting, all the specimens were kept completely immersed in 3.5% NaCl solution and during drying the specimens were kept in air at room temperature. The temperature during drying exposure was approximately 20-30°C (room temperature). The first unit weights of the specimens were determined at 28days just prior to beginning of cyclic exposure, and successive readings were taken immediately after the selected wetting and

drying cycles. The changes in compressive strength after 28, 45 and 90 cycles of exposure were determined by testing the compressive strength of the specimens. The specimens were tested in SSD (saturated-surface-dry) condition and wiped out before testing for compressive strength.

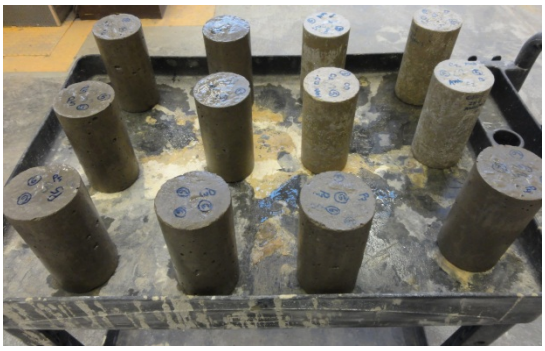


Figure 3-15 Specimens drying in air at room temperature.

3.7. Summary

Manufacture of geopolymer concrete test specimens and the test procedures are described in this chapter. Locally available low calcium fly ash from Collie Power Station was used for making geopolymer concrete. Other ingredients included local coarse and fine aggregates, GGBFS, alkaline solutions, water and superplasticiser. The concrete samples were prepared to determine the mechanical properties such as compressive, tensile and flexural strengths according to Australian Standards. Durability properties such as drying shrinkage, VPV, sorptivity, sulfate resistance and resistance to alternate wetting & drying of concrete were also conducted as per the ASTM and Australian Standards.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Introduction

The results of the tests on ten geopolymer and two OPC concrete mixtures are discussed in this chapter. The geopolymer concrete samples are divided into two series based on the alkaline activator content. Both the geopolymer and OPC concrete samples were tested to investigate the mechanical and durability properties. The durability test included drying shrinkage, VPV (volume of permeable void), sorptivity, sulphate resistance and changes in mass and compressive strength after alternate wetting and drying cycles. Compressive strength, tensile strength and flexural strength were determined at different ages. The effect of inclusion of slag in the binder is discussed with respect to the corresponding control concrete at different test ages.

4.2. Workability of fresh concrete

The workability of fresh geopolymer concrete mixtures was tested by slump test method according to ASTM C 143 (ASTM Standard, 2010) and was determined immediately after mixing of the concrete. Generally, geopolymer concrete mixtures had 'collapse' slump due to its sticky and viscous nature in fresh state. The spherical shape of fly ash particles combined with the lubricating effect of sodium silicate solution increase the flowability and leads to the collapse of the fresh geopolymer concrete. Use of the sodium silicate (SS) and sodium hydroxide (SH) solutions, which are more viscous than water, usually makes geopolymer concrete more cohesive and sticky than OPC concrete. However, a higher slump of geopolymer concrete indicates a less stickiness and higher workability of the mixture.

The workability of the concrete mixtures of series A and B, in terms of the slump value, are shown in Table 4-1 and Figure 4-1. The total alkaline liquid (SS and SH) content of the mixtures of series A was 40% and that of the mixtures of series B was 35%. The effects of the slag content and SS/SH ratio on the workability of the mixtures can be observed from Figure 4-1 and the Table 4-1.

Table 4-1: Slump values of different concrete mixtures.

Mixture	Series	A				B						OPC	
	Mix Id	GPC1	GPC2	GPC3	GPC4	GPC5	GPC6	GPC7	GPC8	GPC9	GPC10	OPC1	OPC2
Label		A40 S10 R2.5	A40 S20 R2.5	A40 S10 R1.5	A40 S20 R1.5	A35 S00 R2.5	A35 S10 R2.5	A35 S20 R2.5	A35 S00 R1.5	A35 S10 R1.5	A35 S20 R1.5		
Slump (mm)		250	195	210	180	245	230	215	235	245	220	105	150

For example, mixture GPC2 with 20% slag showed a slump value of 195 mm as compared to 250 mm slump showed by GPC1 which had 10 % slag. Similarly, mixture GPC4 with SS/SH ration of 1.5 had a slump value of 180 mm as compared to 195 mm slump of mixture GPC2 with SS/SH ratio of 2.5. Mixture GPC4 exhibited the lowest slump value among all the geopolymer concrete mixtures of series A since it had a higher percentage of slag (20%) and a lower SS/SH ratio (1.5) as compared to the other mixtures. Thus, it can be said that the workability of GGBFS blended fly ash geopolymer concrete decreased with the increase of GGBFS content and with the decrease of SS/SH ratio in the mixture.

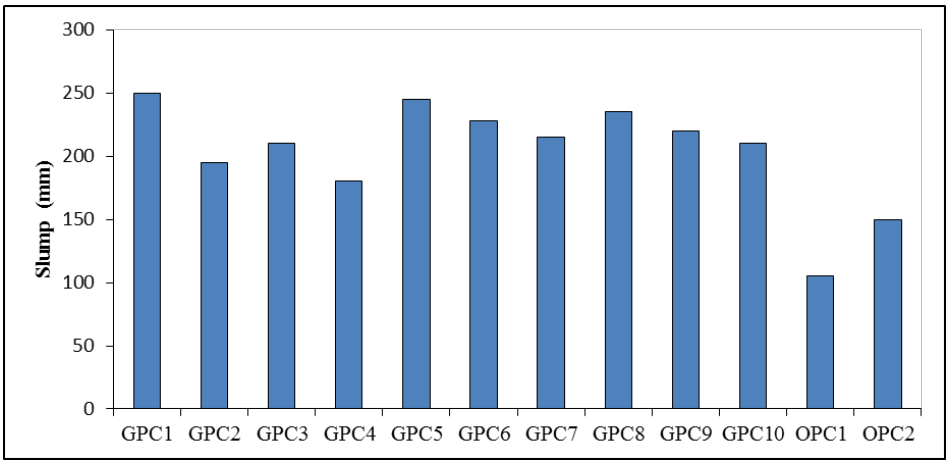


Figure 4-1: Slump of different concrete mixtures.

The geopolymer concrete mixtures of series B, were designed with reduced alkaline activator (35%) than those of series A (40%). Preliminary mixtures with 35% alkaline liquid content showed poor workability as compared to the mixtures of series A. Therefore, extra water (8 kg/m^3) and superplasticiser (6 kg/m^3) were

added to the mixtures of series B in order to improve the workability, as discussed in Section 3.4.1. It is observed that the addition of extra water and super plasticizer in series B was helpful to increase the slump value. The slump values of the mixtures of series B varied between 215 mm and 245 mm. The mixtures were found to have reasonable workability during the casting time.

Generally, when compared with the OPC concrete mixtures, geopolymer concrete mixtures exhibited more cohesiveness than the OPC concrete mixture. No segregation or bleeding was observed in the mixtures during mixing, compaction and finishing of the concrete.

4.3. Mechanical properties of concrete

4.3.1. Compressive strength

Compressive strengths of the geopolymer and OPC concrete mixtures up to 180 days are given in Table 4.2. Strength developments of the concrete mixtures over time are plotted in Figures 4.2 to 4.4.

Table 4-2: Compressive strength results

Mixtures		Label	Compressive Strength (MPa)				
Series	Mix Id		7 day	28 day	56 day	90 day	180 day
A	GPC1	A40 S10 R2.5	27.0	40.0	45.0	47.0	49.0
	GPC2	A40 S20 R2.5	31.0	47.0	50.0	54.0	59.0
	GPC3	A40 S10 R1.5	25.0	43.0	50.0	52.0	54.0
	GPC4	A40 S20 R1.5	29.0	54.0	63.0	68.0	70.0
B	GPC5	A35 S00 R2.5	11.0	25.0	30.0	33.0	35.0
	GPC6	A35 S10 R2.5	15.0	27.0	35.0	38.0	39.0
	GPC7	A35 S20 R2.5	22.0	35.0	40.0	43.0	44.0
	GPC8	A35 S00 R1.5	8.0	27.0	32.0	34.0	37.0
	GPC9	A35 S10 R1.5	14.0	27.0	35.0	41.0	44.0
	GPC10	A35 S20 R1.5	25.0	45.0	52.0	54.0	57.0
OPC		OPC1	36.0	48.0	56.0	62.0	65.0
		OPC2	23.0	33.0	37.0	40.0	43.0

It can be seen from these figures that strength development of the geopolymer concrete mixtures slowed down after the age of 28 days and continued at slower rates until 180 days of age. Comparing the strength developments of the

geopolymer concrete mixtures of both series, it can be seen that the inclusion of 10% and 20% GGBFS in the binder has increased compressive strength.

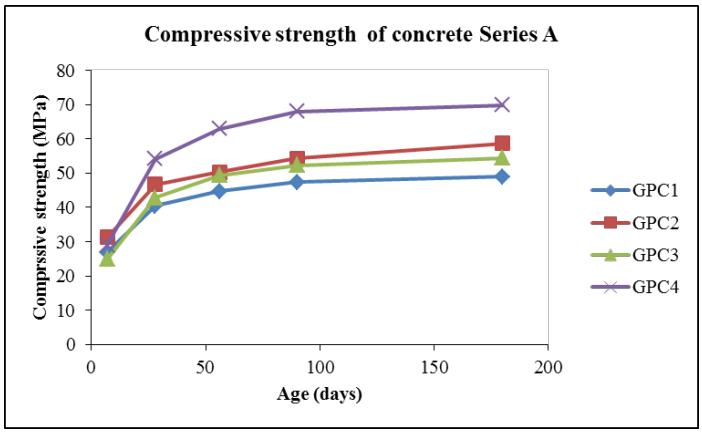


Figure 4-2: Development of compressive strength of geopolymer concrete (Series A)

In series A, mixture GPC2 containing 20% slag achieved 17% higher 28-day compressive strength than GPC1 containing 10% slag. Moreover, the 28-day strength of GPC4 is 15 % higher than that of GPC2. Thus, the effect of slag on the compressive strength appears to be more pronounced when the SS/SH ratio is reduced from 2.5 to 1.5. In Series A, the highest strength increase was achieved in mixture GPC4 with 20% GGBFS and SS/SH ratio of 1.5. Similar strength increase was also observed at 7 days of age with the inclusion of 10 % and 20% of slag in the binder.

In series B, GPC5 with no slag in the binder, developed strength at a slow rate when cured in ambient condition. When GGBFS was incorporated in the mixture as a part of binder with constant alkaline activator of 35% and SS/SH ratio of 2.5, the strength increased significantly. As shown in Figure 4-3, the compressive strength of geopolymer concrete increased from the early age of 7 days and continued to gain strength up to 180 days. At 28 days, mixture GPC6 and GPC7 having 10% and 20% slag respectively, achieved 8% and 40% higher strength, than the geopolymer concrete without slag (GPC5).

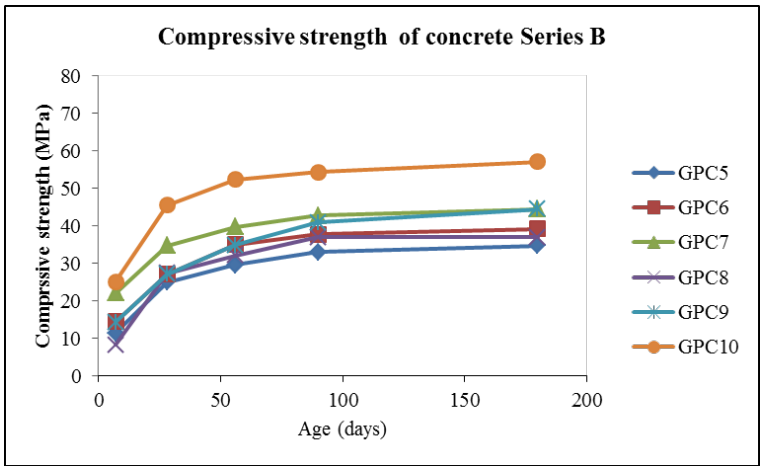


Figure 4-3: Development of compressive strength of geopolymer concrete (Series B)

The improvement of strength of slag blended fly ash based geopolymer concrete is due to the increase of calcium bearing compound in the dissoluted binder which produced reaction product from both slag and fly ash. The strength increase of geopolymer concrete mixtures, GPC9 and GPC10 as compared to GPC8 showed similar trends of GPC5, GPC6 and GPC7. It can be seen that the strength increase is more significant for 20% slag than for 10% slag in the binder. The highest strength increase at all ages up to 180 days was observed for 20% slag and SS/SH ratio of 1.5.

Table 4-3: Water to solids ratio in the concrete mixtures

Mixtures		Label	Water	SP[d]	Na_2O /SiO_2	H_2O /Na_2O	Si/Al	w/s[e]
A	GPC1	A40 S10 R2.5	-	-	0.121	11.745	1.802	0.200
	GPC2	A40 S20 R2.5	-	-	0.125	11.758	1.842	0.200
	GPC3	A40 S10 R1.5	-	-	0.140	10.628	1.757	0.201
	GPC4	A40 S20 R1.5	-	-	0.145	10.639	1.795	0.201
B	GPC5	A35 S00 R2.5	-	6	0.106	11.656	1.730	0.178
	GPC6	A35 S10 R2.5	8	6	0.109	12.764	1.767	0.196
	GPC7	A35 S20 R2.5	8	6	0.112	12.781	1.805	0.196
	GPC8	A35 S00 R1.5	-	6	0.122	10.558	1.695	0.179
	GPC9	A35 S10 R1.5	8	6	0.126	11.540	1.728	0.197
	GPC10	A35 S20 R1.5	8	6	0.130	11.553	1.764	0.197
OPC1		-	165.36	-	-	-	-	-
OPC2		-	201.65	-	-	-	-	-

The Compressive strength of geopolymer concrete is significantly influenced by the amount of alkaline activator in the mixture. Decreasing the activator content from 40% to 35% of the binder without adding any extra water generally increases strength of geopolymer concrete (Nath and Sarker, 2012). Comparing the results of series A and series B, it can be seen that series B with reduced alkaline activator gave less compressive strength than the Series A. The reduction of compressive strength in series B is due to the addition of extra water in the mixtures. The additional water increased the H_2O to Na_2O ratio and also decreased the NaOH concentration in the mixture. From Table 4-3 it can be seen that adding 8 kg/m^3 of extra water in series B increased the H_2O to Na_2O ratio as compared to series A. Previous study indicated that the molar ratio of H_2O to Na_2O significantly influences the compressive strength of fly ash-based geopolymer concrete. An increase in this ratio decreases the compressive strength (Hardjito et al, 2004). Hence, the presence of extra water in series B affected the strength by increasing the molar ratio which caused reduced reactivity for geopolymerisation.

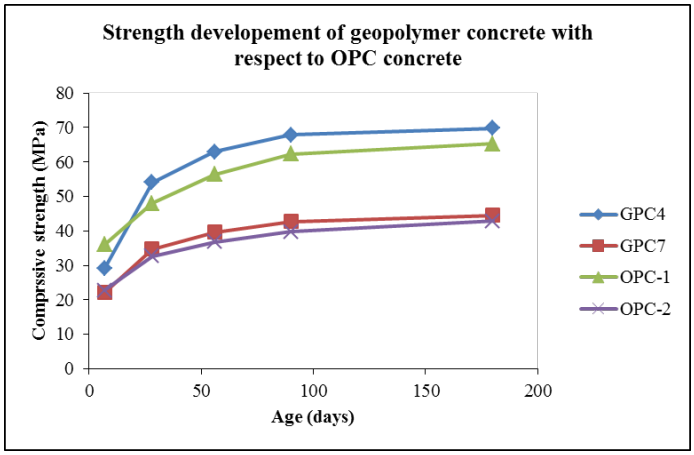


Figure 4-4: Strength development of geopolymer concrete and OPC concrete of similar strength grade.

As shown in Figure 4.4, the strength development rate of geopolymer concrete containing slag in the binder at ambient temperature curing is comparable to that of OPC concrete of similar strength grade.

4.3.2. Indirect tensile strength

The indirect tensile strengths of the geopolymer and OPC concrete samples were experimentally investigated in accordance with AS 1012.10-2000 (Standards Australia, 2000). The average indirect tensile strength values of ten geopolymer and two OPC concrete mixtures at 7, 28 and 90 days are given in Table 4-4.

Table 4-4: Indirect tensile strength results

Mix ID		Label	Indirect tensile strength (MPa)			
Series	Mix ID		7 day	28 day	90 day	Theoretical value at 28 day
A	GPC1	A40 S10 R2.5	2.36	3.09	3.43	2.54
	GPC2	A40 S20 R2.5	2.48	3.25	3.50	2.73
	GPC3	A40 S10 R1.5	1.73	2.88	3.73	2.62
	GPC4	A40 S20 R1.5	2.74	4.81	5.63	2.94
B	GPC5	A35 S00 R2.5	1.35	2.12	2.60	2.00
	GPC6	A35 S10 R2.5	1.43	2.68	2.98	2.08
	GPC7	A35 S20 R2.5	1.43	3.02	3.28	2.36
	GPC8	A35 S00 R1.5	1.00	2.27	2.98	2.09
	GPC9	A35 S10 R1.5	1.25	3.03	3.67	2.08
	GPC10	A35 S20 R1.5	2.14	3.75	4.10	2.70
OPC		OPC1	3.23	4.15	4.26	2.77
		OPC2	3.17	3.43	3.64	2.29

The splitting tensile strengths of the geopolymer concrete for series A are given in Table 4-4. The effect of GGBFS as partial replacement of fly ash on the tensile strength is also shown in Figure. 4-5.

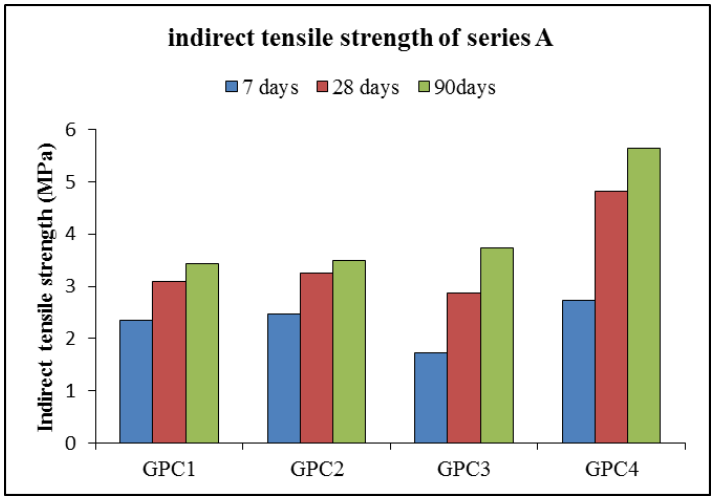


Figure 4-5: Indirect tensile strength of geopolymer concrete (Series A)

It can be seen from Figure. 4-5 that the splitting tensile strength of series A with constant alkaline activator increased with the increase of GGBFS content in the geopolymer mixtures. Moreover, the rate of strength development is high when the ratio of sodium silicate to sodium hydroxide was reduced from 2.5 to 1.5. Geopolymer concrete mixture GPC4 with 20% GGBFS and SS/SH ratio of 1.5 gained 55% higher tensile strength than GPC1 with 10% GGBFS and SS/SH ratio of 2.5.

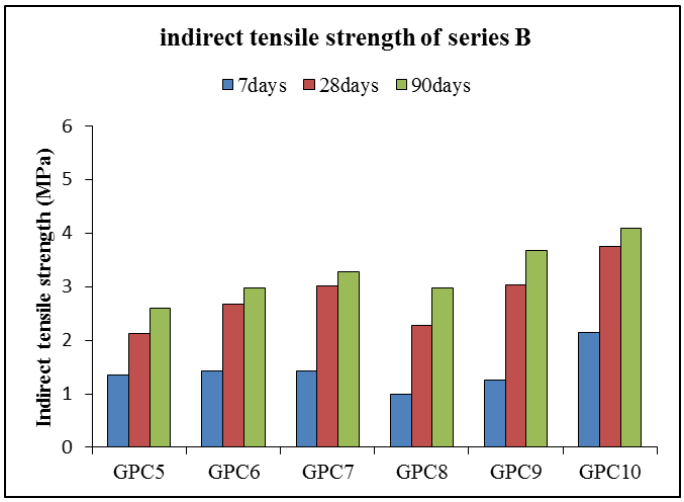


Figure 4-6: Indirect tensile strength of geopolymer concrete (Series B)

In series B, it is observed that the splitting tensile strength development of geopolymer concrete is relatively slow for mixture GPC5 (fly ash only as the binder). When GGBFS was incorporated in the mixture as a part of total binder, with a constant alkaline activator (35%) and SS/SH ratio of 2.5, the tensile strength increased significantly. As shown in Figure 4-6, the strength increased from the early age of 7 days with the increase of slag content in the concretes. At 28 days, mixtures GPC6, GPC7 having 10% and 20% fly ash replaced with GGBFS respectively, achieved 25% and 45% higher strength than GPC5. Moreover, the splitting tensile strength of geopolymer concrete was also influenced by the ratio of sodium hydroxide to sodium silicate in the mixture. Comparing the results of geopolymer mixtures GPC8, GPC9 and GPC10 with GPC5, GPC6 and GPC7 respectively, it can be seen that tensile strength is enhanced with the reduction of SS/SH ratio from 2.5 to 1.5.

Comparing the results of series A and series B, it can be seen that the tensile strength of geopolymer concretes of series B with reduced alkaline activator (35%) decreased from series A due to the addition of extra water in the geopolymer mixtures. The addition of extra water for increasing the workability of geopolymer mixtures decreased the NaOH concentration as well as increased the water to Na_2O ratio in the mixture (Table 4-3). From Table 4-4, geopolymer concrete mixture GPC10 with 35% alkaline activator and extra water exhibited 28% less tensile strength than the GPC4 (40% alkaline activator with no extra water).

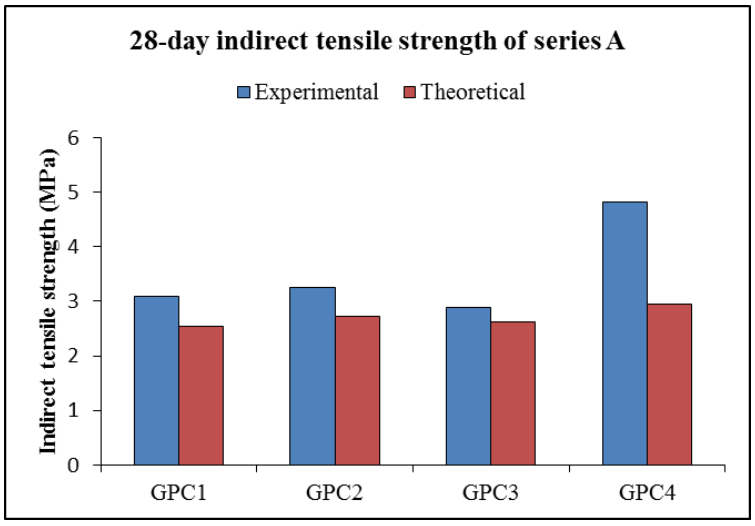


Figure 4-7: Indirect tensile strength of geopolymer concrete at 28days (Series A)

It is also observed from the Figure. 4-7 and 4-8 that the experimentally determined values of tensile strength are higher than the values theoretically predicted by using the AS3600-09 (Standard Australia, 2009) clause 3.1.1.3 based on the 28 days compressive strength for all the geopolymer concrete mixtures. The results show that the formula to predict the tensile strength of concrete in AS3600-09 (Standard Australia, 2009) can be used for conservative prediction of splitting tensile strength of GGBFS blended fly ash based geopolymer concrete.

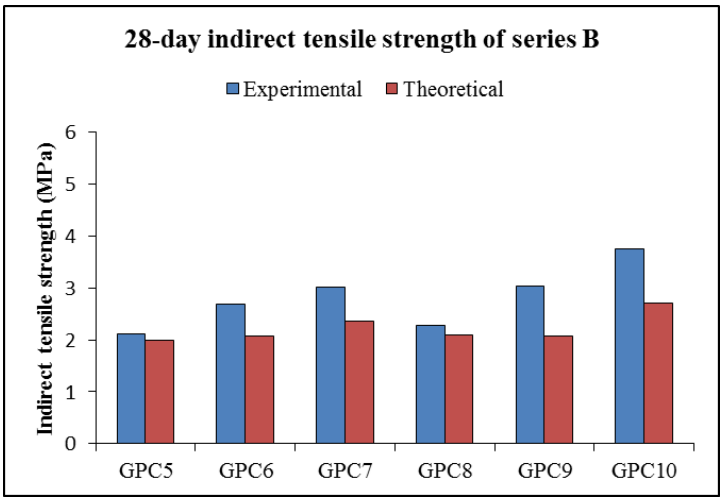


Figure 4-8: Indirect tensile strength of geopolymer concrete at 28days (Series B)

4.3.3. Flexural strength

The flexural strengths of the geopolymer and OPC concrete samples were experimentally determined in accordance with AS 1012.11-2000 (Standard Australia, 2000) using a minimum of two samples per mixture as recommended in the Standard. The flexural strength of the geopolymer concrete increased with increase of age. There is a significant increase in flexural strength at 28 days from the age of 7 days. The increase in flexural strength from 28 days to 90 days of age is relatively small. As shown in Table 4-5, the trend of the increase of flexural strength with age is similar to that of splitting tensile strength.

The average experimental and theoretical flexural strength values (Equation 4-1) of the geopolymer and OPC concrete mixtures at 7, 28 and 90 days of age are given in Table 4-5. The complete test data are given in appendix E.

$$f'_{cf} = 0.60 \times \sqrt{(f'_c)} \qquad \text{---------- (4-1)}$$

Table 4-5: Flexural strength results.

Mix ID		Label	Flexure Strength (MPa)			
Series	Mix ID		7 day	28 day	90 day	Theoretical value at 28 day
A	GPC1	A40 S10 R2.5	3.2	4.68	4.93	3.81
	GPC2	A40 S20 R2.5	3.03	4.92	5.26	4.10
	GPC3	A40 S10 R1.5	3.04	4.98	5.43	3.92
	GPC4	A40 S20 R1.5	3.97	5.15	5.61	4.41
B	GPC5	A35 S00 R2.5	2.67	4.07	4.28	3.00
	GPC6	A35 S10 R2.5	3.17	3.84	4.65	3.12
	GPC7	A35 S20 R2.5	3.03	4.22	4.9	3.53
	GPC8	A35 S00 R1.5	1.87	3.67	4.51	3.14
	GPC9	A35 S10 R1.5	2.46	4.15	4.91	3.12
	GPC10	A35 S20 R1.5	2.85	4.28	5.15	4.04
OPC		OPC1	4.69	4.97	5.26	4.16
		OPC2	3.53	4.14	4.74	3.43

In series A, it can be seen from Figure. 4-9 that the flexural strength of geopolymer concrete varied with the variation of SS/SH ratio and the content of GGBFS in the mixture. The effect of inclusion of GGBFS and the variation of the SS/SH ratio on flexural strength followed the same general trend as the compressive strengths of geopolymer concrete mixtures. Geopolymer concrete mixtures GPC4 with 20% GGBFS and SS/SH ratio 1.5 exhibited highest flexural strength among all the mixtures in series A.

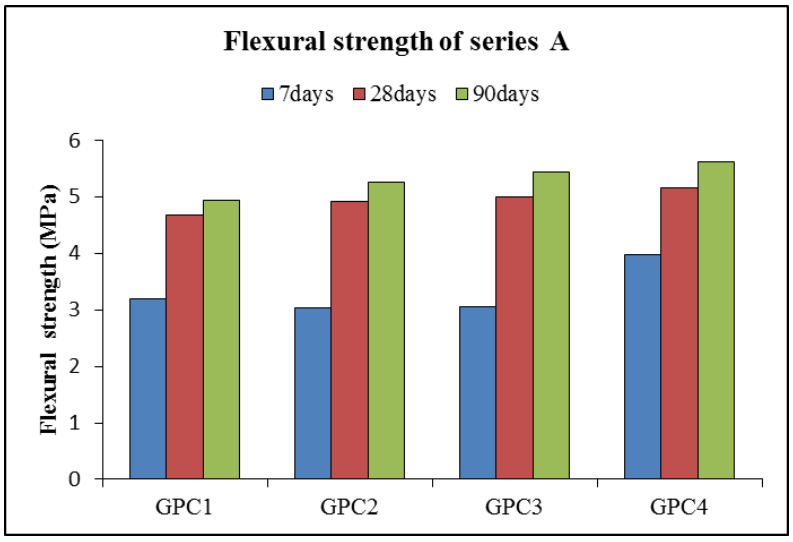


Figure 4-9: Flexural strength of geopolymer concrete (Series A)

In series B, it can be seen that flexural strength of geopolymer concrete increased from the early age of 7 days and continued up to 90 days in a similar way as in series A. The effect of GGBFS on flexural strength can be evaluated by comparing the strengths of the mixtures GPC5, GPC6 and GPC7 with those of mixtures GPC8, GPC9 and GPC10 respectively. It is observed from Figure 4-10 that flexural strength increased with the increase of GGBFS content in the mixture. Also, flexural strength of the mixtures with 35% alkaline activator slightly increased when the ratio of sodium silicate to sodium hydroxide was reduced 2.5 to 1.5. Geopolymer concrete mixture GPC10 with 20% GGBFS and SS/SH ratio 1.5 exhibited 5% higher flexural strength than GPC5 (GGBFS 0% and SS/SH ratio 2.5).

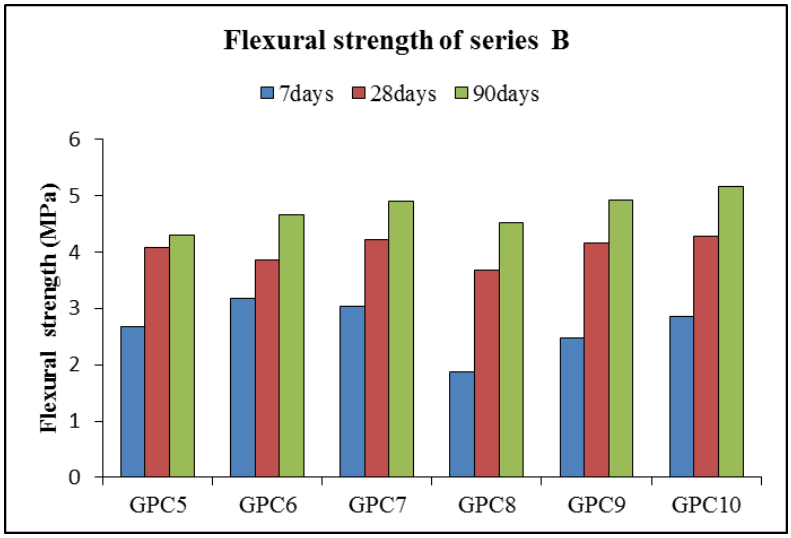


Figure 4-10: Flexural strength of geopolymer concrete (Series B)

Comparing the results of series A and series B, it can be seen that the mixtures of series B with reduced alkaline activator gave less flexural strength than those of series A. for example, Mixture GPC10 designed with 35% alkaline activator and extra water (8 kg/m^3) achieved 4.28 MPa of 28-day flexural strength as compared to 5.15 MPa given by mixture GPC4 with 40% alkaline activator with no extra water. Thus, the effect of inclusion water on the flexural strength of concrete is similar to its effect on compressive strength.

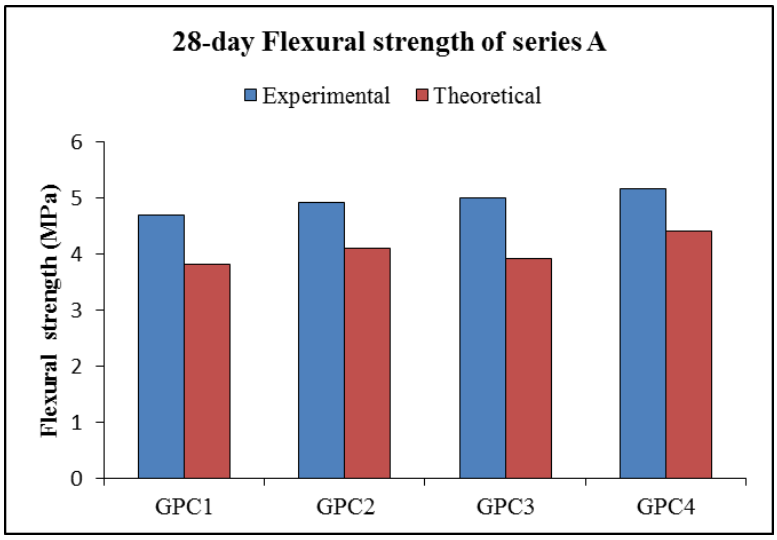


Figure 4-11: Flexural strength of geopolymer concrete at 28-days (Series A)

The 28-day flexural strength values obtained for Series A and Series B were compared with the theoretical values calculated by the equation (Equation. 4-1) of Australian Standard AS3600, clause 3.1.1.3, based on the 28-day compressive strength. The values are given in Table 4-5. All mixtures showed much higher strengths in tests than those predicted by the Equation 4-1. Thus, it shows that the current flexural strength formula given in AS 3600 – 2009 can be used for conservative prediction of flexural strength of GGBFS blended fly-ash based geopolymer concrete.

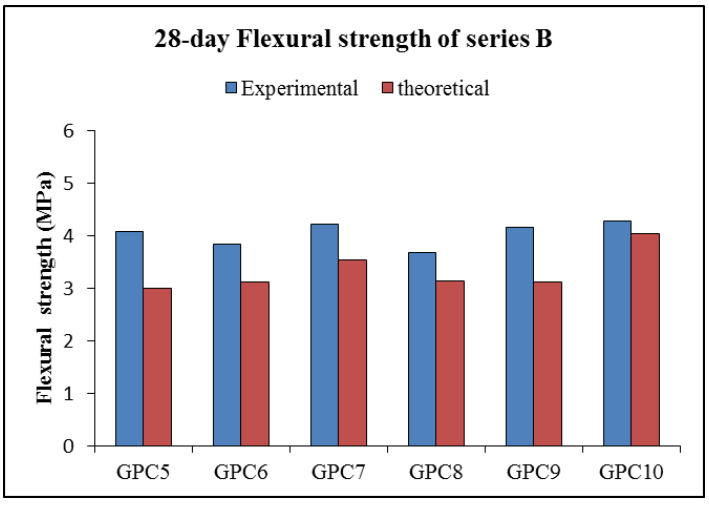


Figure 4-12: Flexural strength of geopolymer concrete at 28-days (Series B)

4.4. Durability properties

4.4.1. Drying shrinkage

The drying shrinkage measurements commenced on the seventh day after casting of concrete specimens. The drying shrinkage values of geopolymer and OPC concrete specimens at different ages are shown in Table 4-6. It can be seen from Table 4-6 that shrinkage continued to occur until 180 days of age in all geopolymer and OPC concrete specimens. The values of shrinkage of all geopolymer concrete specimens at 180 days were well below 1000 microstrain which is the limit for normal and special class concrete specified by the AS1379-2007 standards (Standard Australia, 2007).

Table 4-6: Drying shrinkage results (microstrain).

Mixtures		Label	Drying shrinkage (microstrain)						
Series	Mix Id		14 day	21 day	28 day	56 day	90 day	120 day	180 day
A	GPC1	A40 S10 R2.5	414	527	536	537	555	570	605
	GPC2	A40 S20 R2.5	313	383	419	439	458	476	502
	GPC3	A40 S10 R1.5	281	341	442	488	500	528	542
	GPC4	A40 S20 R1.5	131	250	303	391	411	417	477
B	GPC5	A35 S00 R2.5	504	547	582	606	699	752	814
	GPC6	A35 S10 R2.5	406	435	465	493	531	592	685
	GPC7	A35 S20 R2.5	167	261	290	358	491	502	528
	GPC8	A35 S00 R1.5	694	714	727	745	764	772	802
	GPC9	A35 S10 R1.5	412	489	525	607	632	634	644
	GPC10	A35 S20 R1.5	202	265	320	453	478	510	520
OPC		OPC1	260	318	346	480	512	524	564
		OPC2	270	309	395	465	561	613	625

Previous study by Wallah and Rangan (2006) reported only 100 microstrains of drying shrinkage strain for the heat-cured fly ash based geopolymer concrete specimens. Moreover, the same study also indicated that the ambient-cured geopolymer concrete specimens developed much higher shrinkage than the heat-cured specimens. It is observed from this study that the incorporation of slag in fly ash based geopolymer concrete significantly reduced the drying shrinkage values at ambient-cured condition.

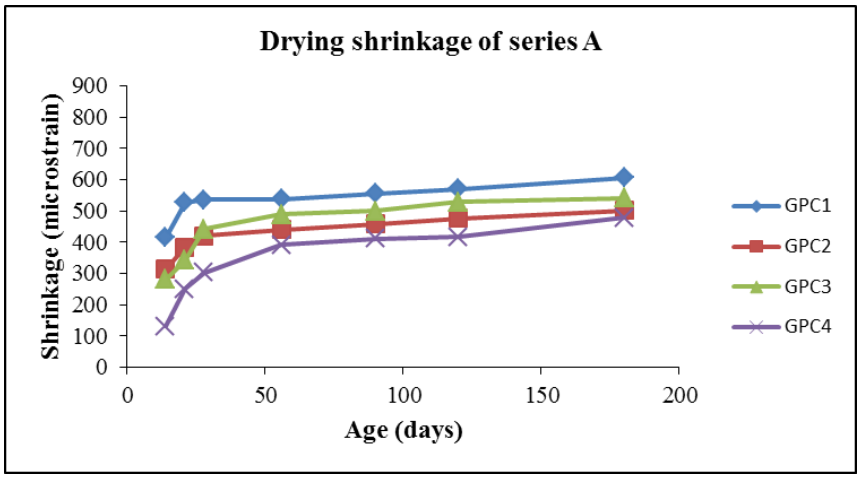


Figure 4-13: Drying shrinkage of geopolymer concrete (Series A)

The drying shrinkage strain versus age of geopolymer concrete specimens of series A are plotted in Figure 4-13. The graphs of Figure 4-13 indicate that the drying shrinkage strains of series A fluctuated slightly over the period of measurement and considerably reduced with the addition of different amount of slag content and SS/SH ratio in the mixtures. The rate of shrinkage for GPC2 (20% slag) reduced almost 20% than GPC1 (10% slag) after 180 days (Table 4-6). Moreover, it is also observed that the rate of drying shrinkage can be further reduced with the reduction of SS/SH ratio from 2.5 to 1.5 in the mixtures. Mixture GPC3 which has the same percentage of slag as in mixture GPC1 exhibited 12% less shrinkage value than GPC1 at 180 days of age. In series A, GPC4 with 20% slag and SS/SH ratio 1.5 showed the lowest value of shrinkage among all the mixtures of series A.

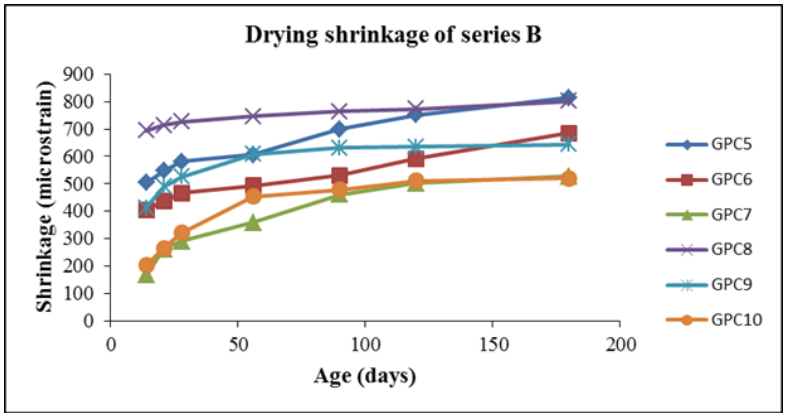


Figure 4-14: Drying shrinkage of geopolymer concrete (Series B)

The drying shrinkage values of the specimens of series B are plotted in Figure 4-14. Comparing the shrinkage values of GPC5, GPC6 and GPC7 and those of GPC8, GPC9 and GPC10, it can be seen that shrinkage reduced by the increase of slag content. Mixture GPC6 (10% slag) and GPC7 (20% slag) achieved 19% and 55% less shrinkage, respectively, than that of GPC5 (no slag). Moreover, in series B geopolymer mixtures GPC10 with the same slag content of GPC7 but reduced SS/SH ratio exhibited less shrinkage value at 180 days.

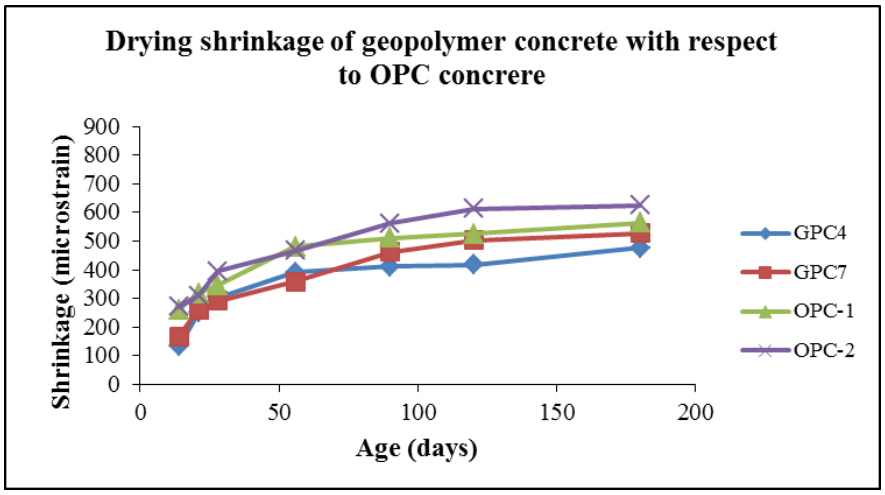


Figure 4-15: Drying shrinkage of geopolymer concrete and OPC concrete specimens.

The shrinkage values of series B which contained extra water were significantly higher than those of series A. In series B, all the mixtures had some extra water which resulted in loss of more free water and hence higher shrinkage than the specimens of series A. For example, at 180 days of age, the shrinkage value of GPC10 of series B is 520 microstrains, whereas that of GPC4 of series A is 477 microstrains. The drying shrinkage values of the OPC concrete and geopolymer concrete specimens of similar strength are plotted in Figure 4-15. It can be seen from this figure that the shrinkage value of GPC7 is much less than that of OPC2 while the two mixtures resulted in similar compressive strengths. Similarly, shrinkage of the mixture GPC4 is less than that of OPC1 which has similar 28-day compressive strength as GPC4.

4.4.2. Volume of permeable voids (VPV)

The volume of permeable voids (VPV) of concretes was determined in accordance with the Australian Standard AS 1012.21-1999 (Standard Australia, 1999). The recommendations of VicRoads to classify concrete quality based on the VPV values are given in Table 4-7. The tests were conducted at different ages in order to understand the effects of incorporation of GGBFS in fly ash based geopolymer concrete. The VPV test results for all geopolymer and OPC concretes at 28 and 180 days are given in Table 4-8.

Table 4-7: VicRoads classification for concrete durability based on the volume of permeable voids (Concrete Institute of Australia, 2001).

VPV (%)	Ratings
<11	Excellent
11-13	Good
13-14	Normal
14-16	Marginal
>16	Bad

Table 4-8: Volume of permeable voids results.

Mixtures		Label	VPV @ 28 days			VPV @ 180 days		
Series	Mix Id		Immersed absorption (%)	Boiled absorption (%)	VPV (%)	Immersed absorption (%)	Boiled absorption (%)	VPV (%)
A	GPC1	A40 S10 R2.5	4.09	4.61	10.88	4.07	4.55	10.71
	GPC2	A40 S20 R2.5	3.97	4.57	10.75	4.19	4.53	10.67
	GPC3	A40 S10 R1.5	3.86	4.53	10.48	3.72	4.31	10.23
	GPC4	A40 S20 R1.5	3.82	4.79	10.28	3.10	3.93	9.27
B	GPC5	A35 S00 R2.5	4.11	4.89	11.38	4.00	4.72	11.02
	GPC6	A35 S10 R2.5	4.16	4.76	11.01	4.16	4.69	10.93
	GPC7	A35 S20 R2.5	4.00	4.75	10.85	3.70	4.68	10.78
	GPC8	A35 S00 R1.5	4.17	4.90	11.16	4.13	4.85	10.95
	GPC9	A35 S10 R1.5	4.02	4.87	10.87	3.82	4.74	10.73
	GPC10	A35 S20 R1.5	3.87	4.63	10.68	4.05	4.56	10.52
OPC		OPC1	5.87	6.01	13.66	5.82	5.85	13.38
		OPC2	6.41	6.55	13.77	6.06	6.04	13.49

Figure 4-16 presents the VPV of different geopolymer concrete mixtures of series A at the ages of 28 days and 180 days. In series A, the trend of the VPV values is seen to be similar to the trend of compressive strengths of the mixtures. The

GGBFS blended fly as based geopolymer concrete exhibited lower VPV values with the increase of GGBFS and decrease of SS/SH ratio in the mixtures. It is noted from Table 4-8 that the VPV value for GPC2 containing 20 % GGBFS decreased from 10.88 to 10.75 due to increment of 10% slag content than GPC1 at 28-days. The reduction of VPV is more enhanced when the SS/SH ratio reduced from 2.5 to 1.5. The VPV value of GPC3 is 4% lower than GPC1 with the same quantity of GGBFS with reduced SS/SH ratio. Moreover, all geopolymer concretes in series A showed lower VPV values at 180 days than those of the specimens cured for 28 days. This was expected as chemical reactions for a longer period resulted in a denser structure of the concrete.

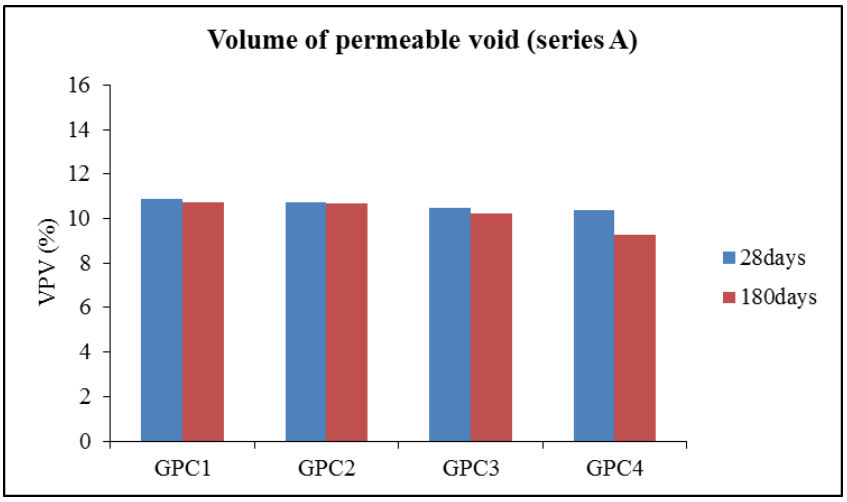


Figure 4-16: Comparison of volume of permeable voids of geopolymer concrete

The test results also indicate that the VPV value of geopolymer concrete are below the limits set by VicRoads in its recommendations for standard concrete. The VPV values of series A are less than 11% which is classified as “excellent” concrete in accordance with the VicRoads classification (Concrete Institute of Australia 2001) for concrete durability based on the VPV of vibrated cylinders (Table 4.7).

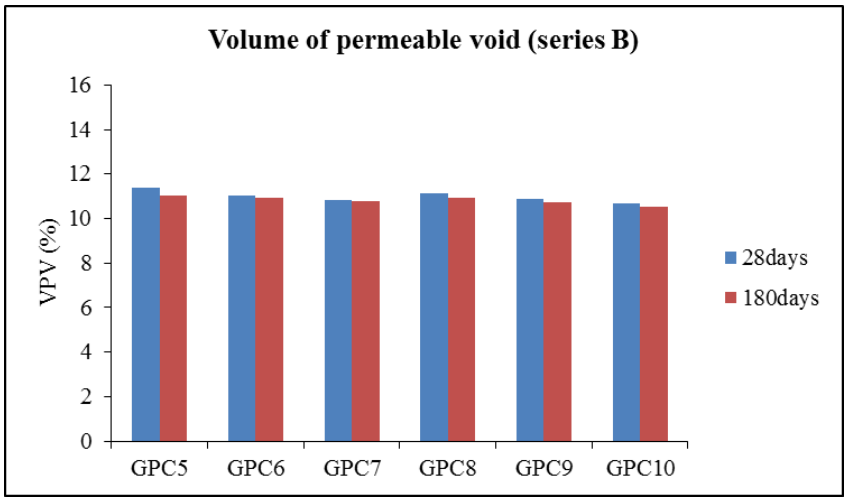


Figure 4-17: Comparison of volume of permeable void of geopolymer concrete

Figure 4-17 and Table 4-8 show that the VPV values of the specimens of series B with reduced alkaline activator content. It is seen from Figure 4-17 that the VPV values slightly decreased with the increase of slag content in the mixtures. The geopolymer concrete mixtures GPC6 and GPC7 containing 10% and 20% slag respectively exhibited 3% and 5% less VPV than mixture GPC5. Moreover, the combined effect of the slag content and the reduced SS/SH ratio showed higher reduction in the VPV values. Thus, the geopolymer concrete GPC8, GPC9 and GPC10 with reduced SS/SH ratio exhibited lower VPV values than GPC5, GPC6 and GPC7, respectively.

The VPV values of GPC6, GPC7, GPC9 and GPC10 are less than 11% and thus are classified as “excellent” concrete according to VicRoads classification for concrete durability based on the VPV of vibrated cylinders (Table 4-7). Mixture GPC5 and GPC8 are just at the margin of 11- 13% which can be classified as a “good” concrete.

Comparing the results of series A and series B, it can be seen that specimens of series B with reduced alkaline activator gave higher VPV values than the series A. As discussed before, the extra water in the geopolymer mixture in series B decreased the concrete compressive strength and increased volume of permeable

voids of the geopolymer matrix as compared to those in series A. When extra water is added, it does not take part in the reaction and fills in the aluminosilicate gel pores (Provis, 2009). Thus, when extra water is used in the mixture, geopolymer produces large gel crystals with trapped water inside (Jaarsveld et al., 2002). Once the water evaporates from the pores, it leaves high amounts of voids and increases the water absorption of the product.

It is observed from Table 4-8 that the VPV values of the geopolymer concrete mixtures were smaller than those of the OPC concrete mixtures. Figure 4-18 shows the comparison between the VPV values of geopolymer concrete and OPC concretes of similar 28-day compressive strength. It can be seen from this Figure that the VPV values of the geopolymer concrete were considerably smaller than those of the OPC concretes of similar strength grade.

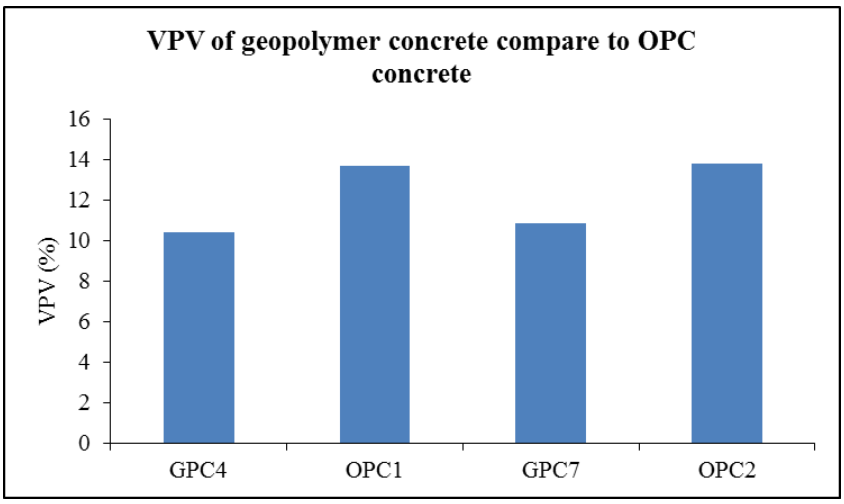


Figure 4-18: VPV of geopolymer concrete and OPC concrete specimens.

4.4.3. Water sorptivity

The measurement of sorptivity has a primary importance in durability assessment of concrete. The rate of water absorption is defined as the slope of the line that is best fit to the absorption plotted against the square root of time. Sorptivity measurements based on the capillary movement of water were conducted on the geopolymer and the OPC concrete specimens. The effect of curing time was

studied by treating the samples in two curing periods, namely 28 days and 180 days. Three specimens from each mixture were tested and the average rate of absorption is reported to the nearest value in mm/min^{½}. Papworth and Grace (1985) recommended the typical values of sorptivity for various performance classes of concrete (Table 4-9). These recommendations are used in this study to rate the quality of geopolymer concrete. The graph and data for all the specimens are given in Appendix J.

Table 4-9: Concrete performance classification (Papworth and Grace, 1985).

Test Methods	Performance Limits		
	Poor	Acceptable	Very Good
Sorptivity (mm/min$^{1/2}$)	>0.2	0.1 to 0.2	<0.1

Table 4-10: Sorptivity test results (mm/min $^{1/2}$).

Mixtures		Label	Sorptivity coefficient (mm/min $^{1/2}$)	
Series	Mix Id		Tested after 28 days	Tested after 180 days
A	GPC1	A40 S10 R2.5	0.099	0.092
	GPC2	A40 S20 R2.5	0.097	0.094
	GPC3	A40 S10 R1.5	0.096	0.090
	GPC4	A40 S20 R1.5	0.094	0.087
B	GPC5	A35 S00 R2.5	0.099	0.098
	GPC6	A35 S10 R2.5	0.095	0.094
	GPC7	A35 S20 R2.5	0.095	0.094
	GPC8	A35 S00 R1.5	0.096	0.095
	GPC9	A35 S10 R1.5	0.094	0.093
	GPC10	A35 S20 R1.5	0.092	0.091
OPC		OPC1	0.159	0.155
		OPC2	0.203	0.190

The water sorptivity values of the specimens of series A are given in Table 4-10. The results are also plotted in Figure 4-19. It can be observed from Figure 4-19 that the rate of water absorption varied with the variation of slag content and SS/SH ratio in the mixtures.

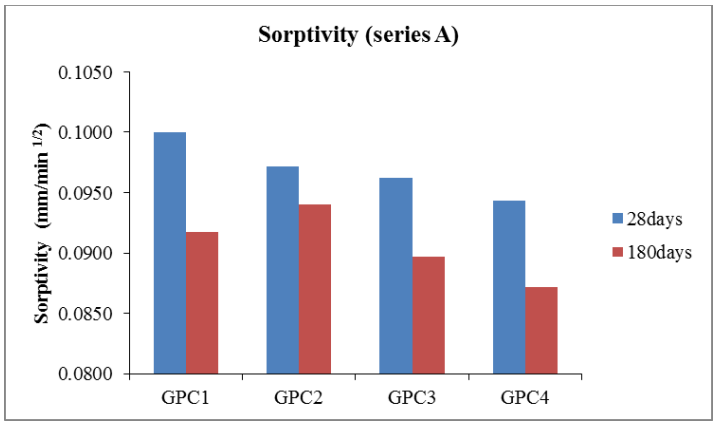


Figure 4-19: Comparison of sorptivity of geopolymer concrete.

Geopolymer concrete mixture GPC2 (20% slag) exhibited lower sorptivity than GPC1 (10% slag) which illustrates the effect of slag content in the binder. Moreover, the sorptivity value further dropped from 0.097 (GPC2) to 0.094 (GPC4) due to reduction of SS/SH ratio in the geopolymer concrete mixtures. Thus, it is seen from the experimental values (Table 4-10) that the rate of water absorption decreased with increase of slag content and decrease of SS/SH ratio in the mixtures. The results indicate that addition of slag has a positive effect on water sorptivity. The pore structure of the geopolymer composite becomes more compact and homogeneous with increase of slag content that has reduced the water sorptivity of the geopolymer concrete. It can also be observed that sorptivity reduced with the increase of curing period from 28 to 180 days.

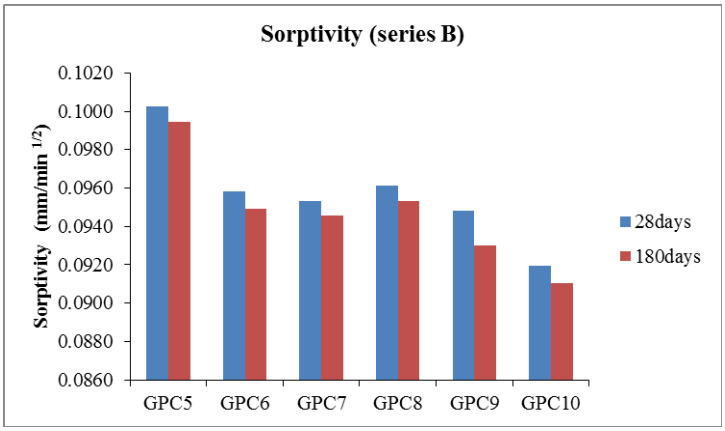


Figure 4-20: Comparison of sorptivity of geopolymer concrete.

The sorptivity results of the geopolymer concrete specimens of series B (Figure 4-20) show that the rate of sorptivity decreased with the inclusion of slag in the binder and with the decrease of SS/SH ratio in the mixtures. The rate of sorptivity for GPC5, GPC6 and GPC7 are 0.099, 0.095, 0.095 mm/min^{½}, respectively. The relatively low sorptivity indicates that there are fewer pores to take up water. The use of slag resulted in a dense matrix and hence a decrease in the rate of sorptivity values as expected. It is noted from Figure 4-20 that mixture GPC6 with 10% slag exhibited less sorptivity than GPC5. The reduction in sorptivity was higher when inclusion of slag in the mixtures was combined with reduced SS/SH in the geopolymer mixtures. GPC10 with 20% slag content and SS/SH ratio 1.5 showed less sorptivity than GPC7 at 28 days. The 180-day sorptivity values were less than the 28-day values. Thus, the effects of slag content and SS/SH ratio on the sorptivity of geopolymer concrete mixtures showed similar trends in both the series.

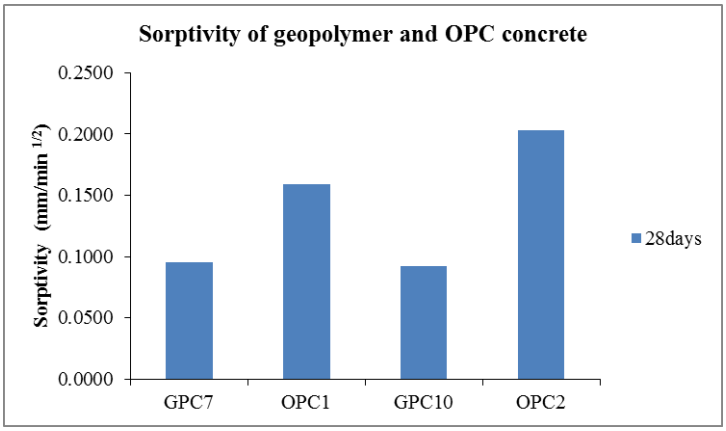


Figure 4-21: Sorptivity of geopolymer concrete and OPC concrete specimens.

Figure 4-21 shows the comparison of sorptivity of different geopolymer and OPC concrete specimens. Recommended values of sorptivity provided by Papworth and Grace (1985) were used to rate the quality of the concrete mixtures. The geopolymer concrete mixtures can be classified as “very good”, since the sorptivity values are less than <0.1 mm/min$^{1/2}$. Geopolymer concrete specimens of mixture GPC7 and GPC10 that achieved similar 28-day compressive strengths of

the mixtures OPC1 and OPC2 respectively have shown significantly lower sorption than the OPC concrete specimens. Thus, the comparison shows that the sorptivity values of the geopolymer concrete mixtures containing GGBFS were smaller than those of OPC concrete of similar compressive strengths.

4.4.4. Sulphate resistance

4.4.4.1. Visual appearance

Visual inspections of the geopolymer and OPC concrete specimens were done after 56 days, 90 days and 180 days of exposure in sulphate solution. Figure 4-22 shows the visual appearance of typical geopolymer and OPC concrete specimens. There were no signs of cracking, disintegration or change in external appearance in the geopolymer concrete specimens. On the other hand, the surfaces of OPC concrete specimens soaked in sulphate solution started to erode after 90 days of exposure and cracks developed after 180 days of sulphate exposure.

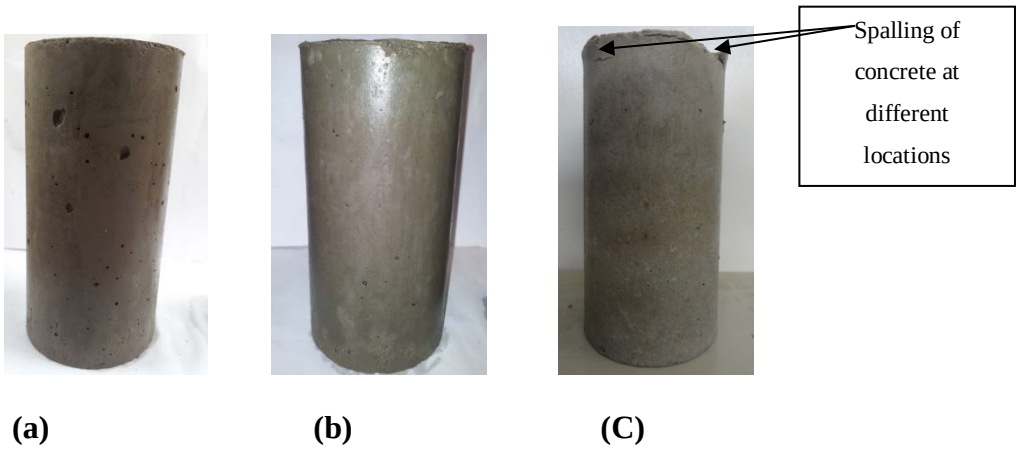


Figure 4-22 Visual appearance of concrete specimens after 180 days of exposure (a) geopolymer concrete sample cured in ambient condition (b) geopolymer concrete sample soaked in 5% sodium sulphate solution (C) OPC concrete sample soaked in 5% sodium sulphate solution.

4.4.4.2. Mass change

The changes in mass of the concrete cylinders were measured for different period of exposure to sulphate solution. The mass changes of geopolymer (GPC4 and GPC7) and OPC concrete specimens in sodium sulphate solution are presented in Figure 4-23.

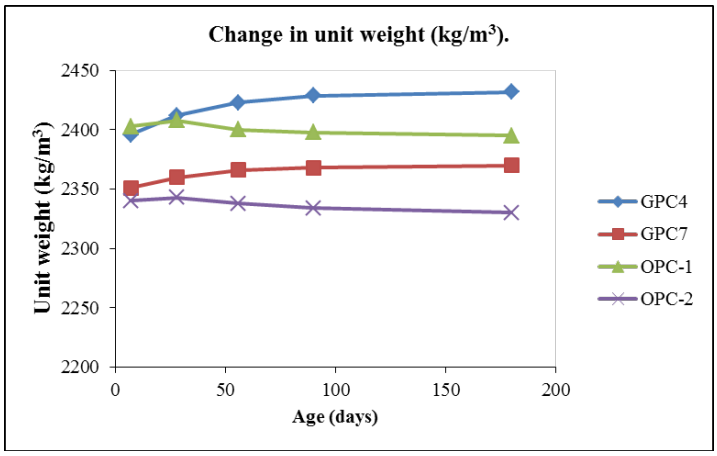


Figure 4-23 Change in unit weight of geopolymer and OPC concrete specimens soaked in 5% sodium sulphate solution.

A slight mass gain during the first week of exposure was observed in the specimens due to the absorbed solution by concrete. The trend of mass gain is similar for the geopolymer concrete specimens of series A and B. The average unit weight of geopolymer concrete cured in ambient conditions was 2375 kg/m^3. It can be seen from the figure that unlike the OPC concrete specimens, the geopolymer concrete specimens did not lose any mass in exposure of the sulphate solution. This indicates that unlike OPC concrete, geopolymer concrete did not suffer from any erosion when exposed to the sulphate solution. Thus, the results show the stability of the geopolymer concrete mass in sulphate solution.

4.4.4.3. Change in compressive strength

Change in compressive strength was determined by testing the specimens after 56 days, 90 days and 180 days of immersion in 5% sodium sulphate solution. The

compressive strength results of the concrete specimens after different periods of exposure are given in Table 4-11.

Table 4-11: Compressive strength of concrete at sulphate solution.

Mixtures		Compressive Strength (MPa)									
		28 day	56 day			90 day			180 day		
Series	Mix Id	ambient curing	ambient curing	sodium sulphate solution	% of change in strength (28days)	ambient curing	sodium sulphate solution	% of change in strength (28days)	ambient curing	sodium sulphate solution	% of change in strength (28days)
A	GPC1	40	45	47	17	47	52	30	49	54	35
	GPC3	43	50	51	18	52	53	23	54	56	30
	GPC4	54	63	64	18	68	69	27	70	72	33
B	GPC5	25	30	30	20	33	34	36	35	36	44
	GPC6	27	35	36	33	38	38	40	39	41	51
	GPC7	35	40	42	20	43	53	51	44	56	60
	GPC9	27	35	36	33	41	41	52	44	45	67
OPC1		48	56	60	25	62	61	27	65	43	-10.
OPC2		32	37	39	21	40	39	21	43	26	-23.

Because of the limitation of space for immersion in sulphate solution, only some selected mixtures were used to make test specimens. Three mixtures (GPC1, GPC3 and GPC4) from series A, four mixtures (GPC5, GPC6, GPC7 and GPC9) from series B and two OPC mixtures of similar strength were chosen for compressive strength tests. For comparison the change in compressive strength in sulphate solution, a set of concrete specimens from the same batch cured at ambient condition was also prepared and tested for compressive strength at 56 days, 90 days and 180 days after casting. The compressive strengths of these specimens without any exposure were taken as the reference strengths for comparison.

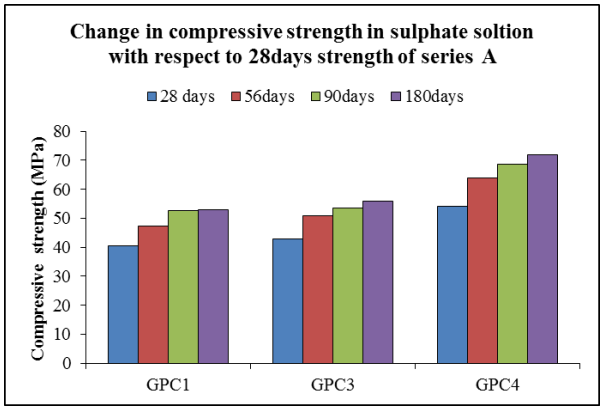


Figure 4-24 Compressive strength of geopolymer concrete (series A) after 180 days of exposure

Figures 4-24 and 4-25 show the compressive strengths of the geopolymer concrete specimens of series A and series B soaked in sodium sulphate solution for the exposure periods of 56 days, 90 days and 180 days respectively. The 28-day compressive strengths of the specimens are also plotted in these figures. It can be seen from the compressive strength values of Table 4-11 that the period of exposure up to 180 days does not have any considerable effect on the compressive strength of geopolymer concretes. Strength of the geopolymer concrete specimens of both series increased over time in a similar manner whether or not the specimens were immersed in the sulphate solution.

Over the 180 days of immersion, compressive strength of series A and series B exhibited 30-67% strength increase compared to the strength of specimens cured in ambient condition for 28 days. The highest strength increases of the geopolymer concrete were observed in mixtures GPC7 and GPC9 with 10 and 20 % slag content, where strength increases were 60% and 67% respectively. The compressive strength of GPC7 after 180 days of exposure in sodium sulphate solution was 56 MPa as compared to 35 MPa at 28 days of age. The rest of the mixtures of series A and B showed the same trend as GPC7 and GPC9, and exhibited higher strength in sulphate solution compared to the same specimens cured at ambient condition (Table 4-11).

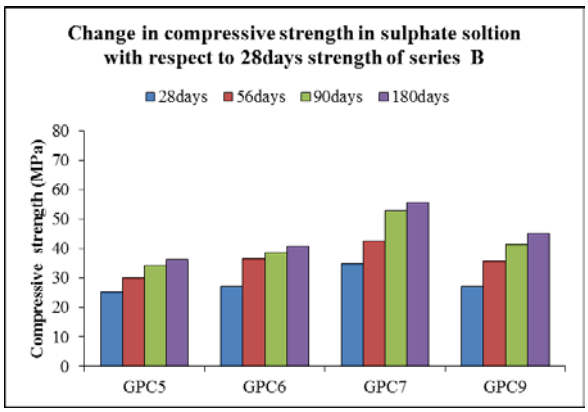


Figure 4-25 Compressive strength of geopolymer concrete (series B) after 180 days of exposure

The compressive strengths of the similar strength grade geopolymer and OPC concrete specimens after immersion in sodium sulphate solution up to 180 days are plotted in Figure 4-26. It can be seen from this figure that the OPC concrete mixtures that achieved similar strength of geopolymer concrete at 28 days exhibited strength reduction after 180 days of sulphate exposure. In sulphate solution, strength of OPC concrete specimens increased in the first month of the immersion and then had a steady decline. After 5 months of immersion, the loss of strength was up to 10-23% for the OPC concrete specimens. While OPC concrete lost compressive strength, the geopolymer concrete specimens gained strength in the sodium sulphate solution.

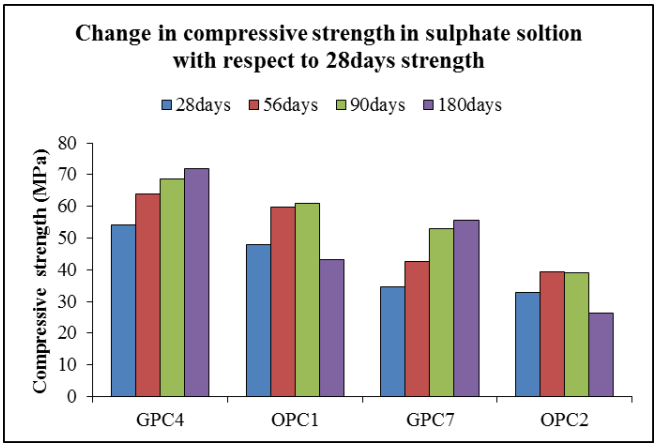


Figure 4-26 Compressive strength of geopolymer concrete and similar strength OPC concrete specimen after 180 days of exposure.

Many of the durability issues of OPC concrete are associated in one way or another with the calcium content of its main phases. Sulphate attack by ions in the soil as well as in ground and seawater deteriorates reinforced concrete structures, for instance. In hardened cement paste, C_3A reacts with sulphate ions in the presence of $Ca(OH)_2$ to form ettringite and gypsum, leading to the disruptive expansion of concrete and its degradation into a non-cohesive granular mass. Previous investigations indicated that heat-cured fly ash based geopolymer concrete specimens were more resistant to sulphate attack as compared to OPC concrete (Wallah and Rangan, 2006). Fly ash-based geopolymer concrete undergoes a different mechanism to that of Portland cement concrete and the geopolymerisation products are different from hydration products. Unlike the hydration products, the main product of geopolymerisation is not susceptible to sulphate attack. For this reason, the geopolymer concrete specimens did not show signs of deterioration after immersion in sulphate solution up to 180 days.

4.4.4.4. Change in length

The changes of length of the geopolymer and OPC concrete specimens subjected to 5% Na_2SO_4 solution are given in Table 4-12. According to ACI code (ACI 201.2R-08), the recommended expansion for a concrete having a blend of sulphate resisting cement and pozzolanaic binders is less than 0.05% after 6 months and less than 0.1% after one year (Clifton, J. et al,1999). Moreover, Tikalsky and Carasquillo (1992) considered an expansion in the order of 0.05% as a failure of concrete samples under sulphate attack.

Previous research showed that the change in length of heat-cured geopolymer concrete specimens soaked in sodium sulphate solution for various periods of exposure was less than 0.01% (Wallah and Rangan, 2006). The maximum expansion in the current study was found to be 0.0054% for the mixture GPC5 at 180 days of immersion.

Table 4-12: Percentage of length change in sulphate solution exposure.

Mixtures		Label	Length change (%)						
Series	Mix Id		14day	21 day	28 day	56day	90day	120day	180day
A	GPC1	A40 S10 R2.5	-0.0019	0.00106	0.00128	0.00221	0.00261	0.0035	0.0041
	GPC3	A40 S10 R1.5	0.0009	0.0010	0.0011	0.0011	0.0016	0.0024	0.0035
	GPC4	A40 S20 R1.5	-0.0041	-0.0036	-0.0034	0.0002	0.0013	0.0020	0.0027
B	GPC5	A35 S00 R2.5	-0.0005	0.0001	0.0015	0.0022	0.0034	0.0043	0.0054
	GPC6	A35 S10 R2.5	-0.0056	-0.0038	-0.0021	-0.0013	0.0025	0.0033	0.0048
	GPC7	A35 S20 R2.5	-0.0007	0.0003	0.0011	0.0020	0.0022	0.0032	0.0044
	GPC9	A35 S10 R1.5	-0.0046	-0.0031	-0.0022	-0.0008	0.0012	0.0023	0.0038
OPC		OPC1	-0.0023	-0.0055	-0.0059	-0.0071	0.0121	0.0213	0.0286
		OPC2	-0.0030	-0.0040	-0.0068	0.0018	0.0091	0.0386	0.0538

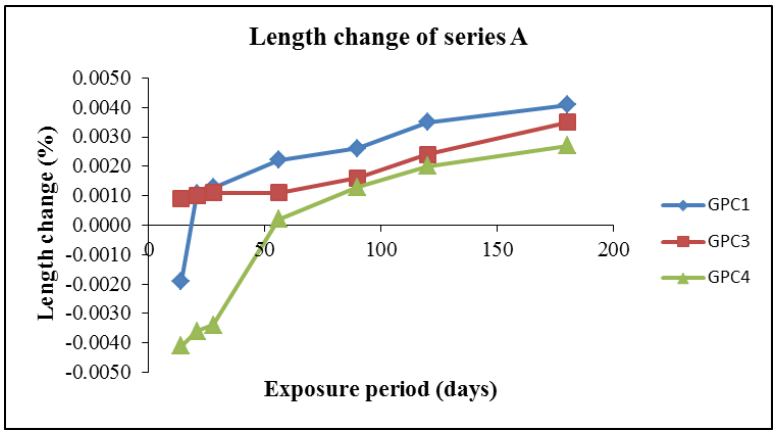


Figure 4-27: Length change of geopolymer concrete (Series A)

In the sulphate solution, the geopolymer concrete specimens showed some shrinkage in the first month of immersion and then they showed expansion which continued up to 180 days. The length changes of the specimens with continued immersion in sulphate solution are plotted in Figures 4-27 and 4-28.

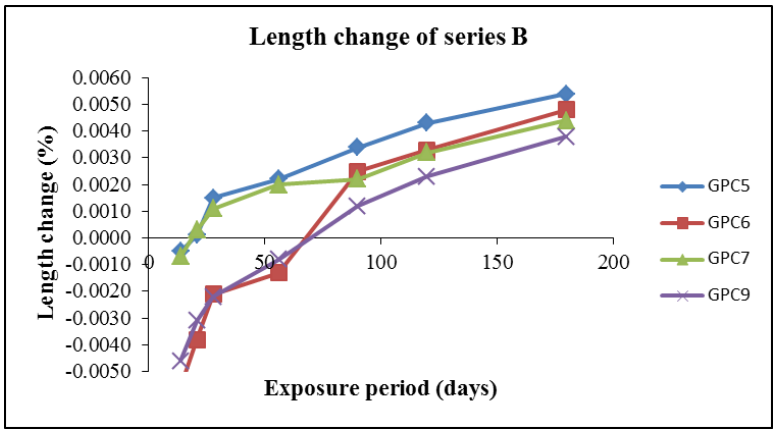


Figure 4-28: Length change of geopolymer concrete (Series B)

It can be seen from the graphs of series B, that the use of slag reduced the expansion of mixture GPC6 at 180 days of immersion as compared to GPC7. The reduction of SS/SH ratio from 2.5 to 1.5 in GPC9 with the same slag quantity as GPC6 further reduced the expansion at the same age. The expansions of series B which contained extra water are higher than those of series A (Table 4-12). After immersion for 180 days, the expansions of GPC1 (series A) was less than GPC6 (series B). The expansions of the specimens of both series after 180 days of immersion were well below 0.05% that is considered as failure by Tikalsky and Carasquillo (1992).

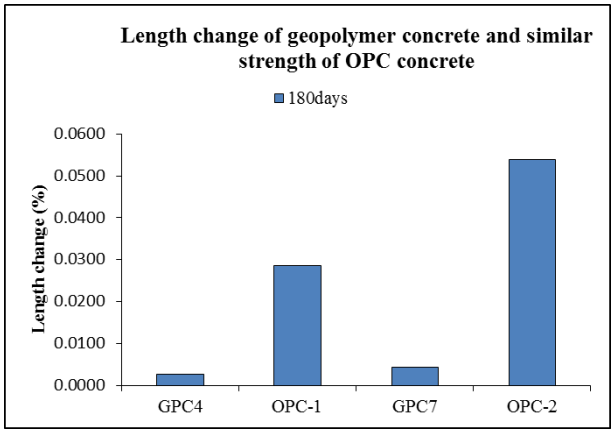


Figure 4-29: Length change of geopolymer and similar strength of OPC concrete specimens.

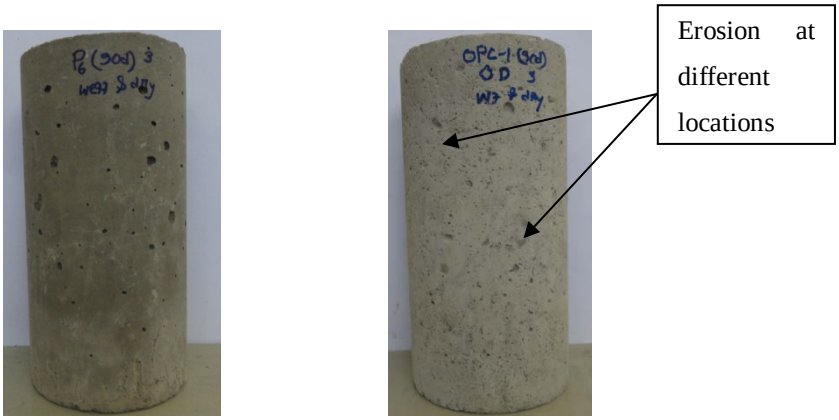
Test results on the change in length of the similar strength geopolymer and OPC concrete specimens soaked in sodium sulphate solution up to 180 days are

presented in Figure 4-29. Previous study by Wee et al (2000) observed that the change in length of Portland cement concrete with water to binder ratio of 0.4 to 0.5 was about 0.035 to 0.1% after 224 days of immersion in 5% sodium sulphate solution. It can be seen from the experimental values (Table 4-12) that the mixture OPC2 that achieved similar strength of geopolymer concrete GPC7 at 28 days exhibited higher expansion value than 0.05% after 180 days of sulphate exposure. Generally, the results show that the expansion of the geopolymer concrete was much less than the OPC concrete specimens. Also, inclusion of slag further reduced the expansion of geopolymer concrete.

4.4.5. Alternative wetting and drying

4.4.5.1. Visual appearance

The change in the appearance of the geopolymer and OPC concrete specimens after 28, 45 and 90 cycles of alternating wetting and drying were observed. The appearance of geopolymer and OPC concrete test specimens subjected to repeated wetting and drying for 28, 45 and 90 cycles are shown in Figure 4-30.



(a) **(b)**

Figure 4-30: Specimens after 90 cycles of exposure in 3.5% sodium chloride solution (a) geopolymer concrete (b) OPC concrete.

It can be seen that the geopolymer concrete specimens exposed to alternate wetting and drying exhibited no sign of cracking, erosion or disintegration on the surface, as shown in Figure 4-30. On the other hand, some erosion on the surface

of OPC concrete specimens was observed after 90 cycles of alternate wetting and drying.

4.4.5.2. Mass change

The cavities and pores of the concrete specimens are filled with salt solution and crystallization of salts occur in the pores in the alternate wetting and drying cycles causing a change in mass. Changes in mass of the geopolymer and OPC concrete specimens were measured after different number of cycles of alternate wetting and drying. Weight losses of geopolymer (GPC4 and GPC5) and OPC (OPC1 and OPC2) concrete specimens after 7, 28, 45,56 and 90 cycles of alternate wetting and drying (Oven dry and ambient dry) are shown in Figures 4-31 and 4-32 respectively.

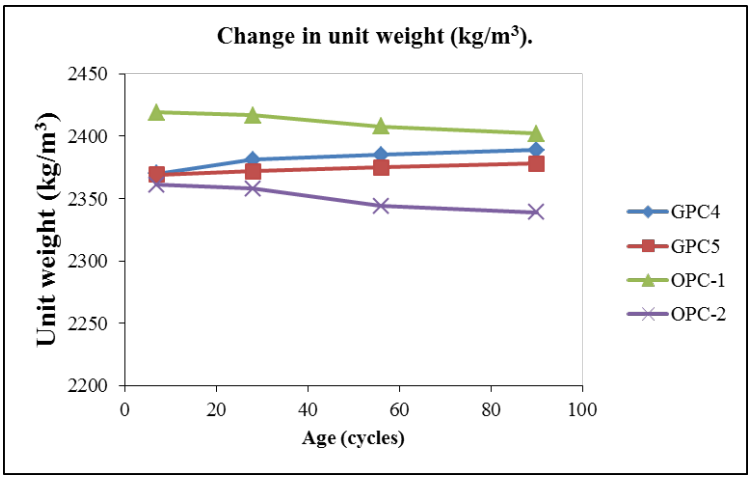


Figure 4-31 Unit weight of geopolymer and OPC concrete specimens after alternate wetting and drying (oven dry).

Initially, evaporation for OPC concrete samples during drying was greater than the water absorption that caused the weight loss during the first 20 cycles compared to geopolymer concrete specimens. Weight loss can be observed for both OPC and geopolymer concrete specimens in the case of alternate wetting and drying at oven dry conditions. However, the weight loss for geopolymer concrete is not significant compared to weight loss of OPC concrete. On the other hand, weight of the geopolymer concrete specimens remained same over the alternate wet and drying cycles at ambient condition. This shows the stability of the

ambient temperature cured geopolymer concrete specimens under alternate wet and dry cycles (ambient conditions). The small weight losses of the OPC concrete specimens are because of some erosion on the surface, as shown in Figure 4.30 (b).

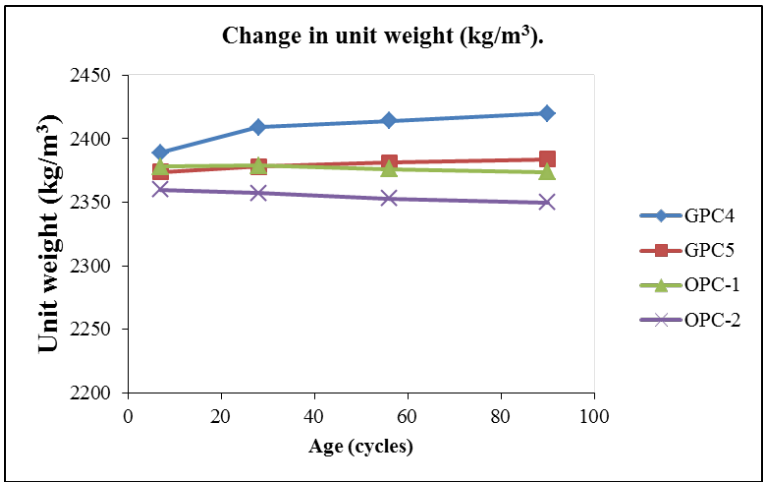


Figure 4-32 Unit weight of geopolymer and OPC concrete specimens after alternate wetting and drying (ambient dry).

4.4.5.3. Change in compressive strength

The compressive strength of geopolymer and OPC concrete specimens were determined after 28, 45 and 90 cycles of alternate wetting and drying. Two different methods were used for the drying cycle. In the first method, the drying cycle consisted of drying the specimens in an oven at 80^0C for 24 hours. This method of drying was used because this is considered as a severe situation of drying. This method of drying cycle was used in other previous studies of OPC and geopolymer concrete (Kasai and Nakamura, 1980; Olivia and Nikraz, 2012). Since drying at a high temperature such as 80^0C is expected to increase the compressive strength of geopolymer concrete, a second series of test was conducted by drying the samples in air at ambient temperature (25-35^0C). Four geopolymer (GPC3, GPC4, GPC5 and GPC6) and two OPC (OPC1, OPC2) concrete mixtures were chosen for the first method. Three mixtures (GPC1, GPC3 and GPC4) from series A, four mixtures (GPC5, GPC6, GPC7 and GPC9) from series B and two OPC mixtures of similar compressive strength were chosen for

the second method of wetting and drying cycles. For comparison, the change in compressive strength in sodium cholirde solution a set of concrete specimens from the same batch continuously cured at ambient condition was also prepared and tested for compressive strength at the same age. The compressive strength of these specimens without any wetting and drying was taken as the reference compressive strength. The compressive strengths of the specimens for the two different methods of drying in the alternate wetting and drying cycles are described below.

Table 4-13: Compressive strength after alternate wetting and drying cycles (drying at 80 ^{0}C).

Mixtures		Compressive strength (MPa)									
Series	Mix Id	28 days	28 cycles			45 cycles			90 cycles		
		ambient curing	ambient curing	Alternate wetting & drying	% of change in strength (28days)	ambient curing	Alternate wetting & drying	% of change in strength (28days)	ambient curing	Alternate wetting & drying	% of change in strength (28days)
A	GPC3	43	49	59	37	52	61	42	54	63	47
	GPC4	54	63	68	26	68	70	27	70	72	33
B	GPC5	25	29	39	56	33	41	64	35	43	72
	GPC6	27	35	44	63	38	48	78	39	53	96
OPC1		48	56	55	14	62	60	25	65	51	6
OPC2		33	37	33	0	40	36	9	43	31	-6

Drying in an oven at elevated temperature

The compressive strengths of the concrete specimens after different cycles of alternate wetting and drying are given in Table 4-13 and plotted in Figure 4-33. It can be seen from the results in Table 4-13 that significant strength increase occurred in the geopolymer concrete specimens after the alternate wetting and drying in an oven at 80^{0}C. The increase in compressive strength after 28 cycles of wetting and drying ranged from 26 to 65% in the geopolymer concrete specimens and it ranged from 2 to 14% in the OPC concrete specimens. The strength increase in both types of concrete after 28 cycles is mainly due to further curing the concrete at an elevated temperature. The extent of strength increase is higher in

geopolymer concrete than in OPC concrete. This is because of the greater effect of elevated temperature on the curing of geopolymer concrete than on OPC concrete. After 90 cycles of wetting and drying cycles, the strength increase of the geopolymer concrete specimens as compared to their 28-day strength varied from 33 to 96%.

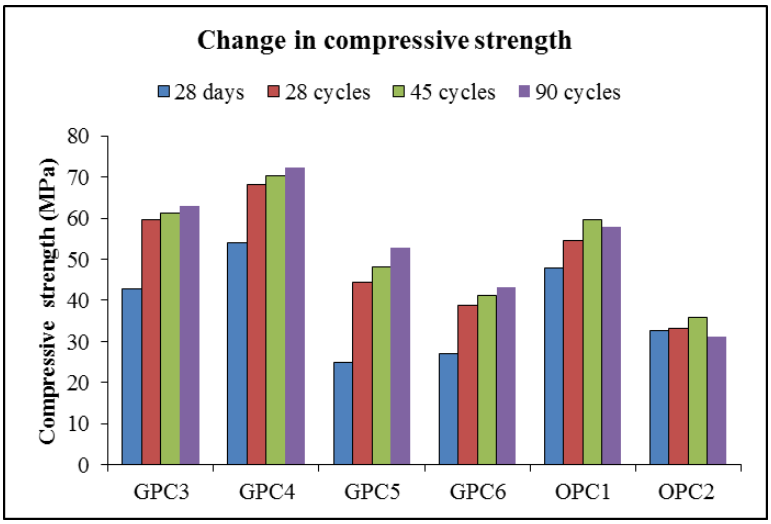


Figure 4-33 Compressive strength of geopolymer concrete and similar strength OPC concrete specimen after 90 cycles of alternate wetting and drying.

Geopolymer concrete mixture GPC3 showed 37% strength increase after 28 cycles and the strength increment reached up to 47% after 90 cycles of exposure. The other geopolymer mixtures also showed the same trend as GPC3 until the 90 cycles of wetting and drying. A relatively small increase or decrease of the strength was observed in the OPC concrete specimens after 90 cycles of wetting and drying. It can be seen from Table 4-13 that the OPC concrete mixture that achieved similar strength of geopolymer concrete at 28 days, exhibited strength reduction at the end of the exposure period. After 90 cycles of alternate wetting and drying, the specimens of mixture OPC2 showed 6% reduction of strength than the 28-day compressive strength.

Drying at ambient condition

The compressive strengths of geopolymer and OPC concrete specimens subjected to continuous cycles of immersions in sodium chloride solution and drying in ambient condition are given in Table 4-14. The drying of the specimens was carried out in air with temperature varying between 25 and 35 ^{0}C. The values are plotted in Figures 4-34, 4-35 and 4-36.

Table 4-14: Compressive strength of concrete due to alternate wetting and drying (25-35^{0}C).

Mixtures		Compressive strength (MPa)									
		28 days	28 cycles			45 cycles			90 cycles		
Series	Mix Id	ambient curing	ambient curing	wetting and drying	% of change in strength (28days)	ambient curing	wetting and drying	% of change in strength (28days)	ambient curing	wetting and drying	% of change in strength (28days)
A	GPC1	40	45	46	15	47	49	22	49	50	25
	GPC3	43	49	48	12	52	55	28	54	65	51
	GPC4	54	63	62	15	68	68	26	70	72	33
B	GPC5	25	29	28	12	33	33	32	35	35	40
	GPC6	27	35	33	22	38	37	37	39	42	55
	GPC7	35	40	43	23	43	44	26	44	47	34
	GPC9	27	35	34	26	41	42	56	44	44	63
OPC1		48	56	55	15	17	59	30	65	57	19
OPC2		33	37	39	18	12	42	27	43	36	10

Figures 4-34 and 4-35 show that the compressive strength of geopolymer concrete specimens increased after 28 cycles and continued to increase until 90 cycles of wetting and drying. However, the rate of strength increment was less for ambient dried specimens as compared to oven dried specimens. For example, after 90 cycles of wetting and drying, the strength gain of geopolymer mixture GPC6 was 55% when the drying was done in ambient condition as compared to 95% strength gain when the drying was done in an oven at 80 ^{0}C.

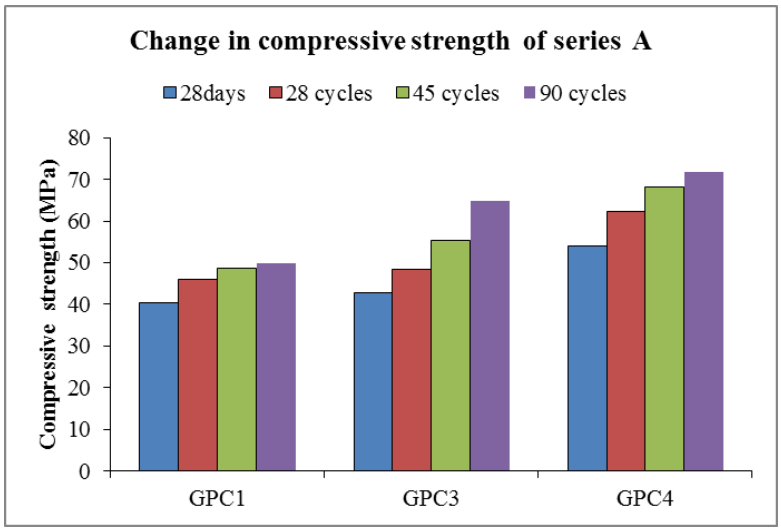


Figure 4-34 Compressive strength of geopolymer concrete (series A) after alternate wetting and drying cycles.

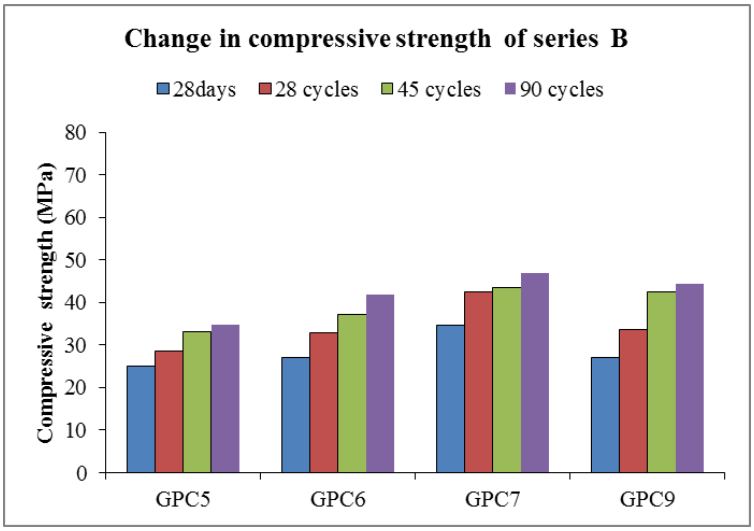


Figure 4-35 Compressive strength of geopolymer concrete (series B) after alternate wetting and drying cycles.

As shown in Figure 4-36, the OPC concrete specimens which achieved similar strength of geopolymer concrete at 28 days showed decline of strength reduction after 90 cycles of alternate wetting and drying.

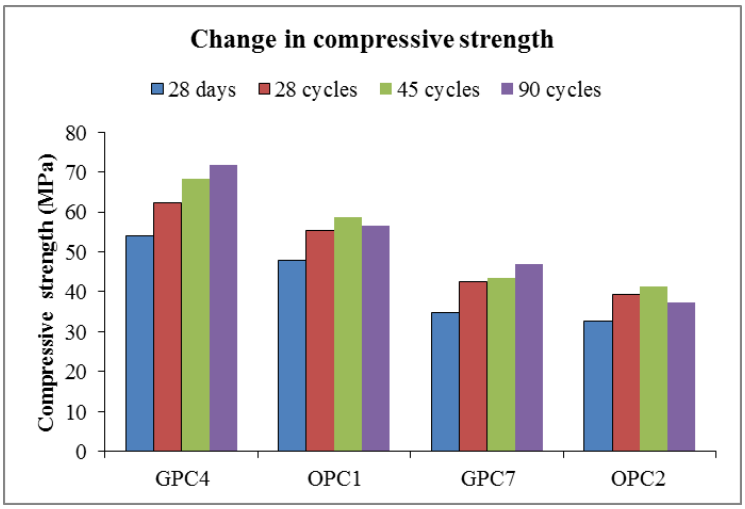


Figure 4-36 Compressive strength of geopolymer concrete and similar strength OPC concrete specimen after alternate wetting and drying cycles.

For both types of drying conditions, after 90 cycles of alternate wetting and drying, the geopolymer concrete specimens showed continued strength gain while the OPC concrete specimens showed decline in the strength. Thus, the comparison shows better performance of the geopolymer concrete specimens as compared to the OPC concrete specimens in the test conditions.

4.5. Summary

Inclusion of ground granulated blast furnace slag (GGBFS) together with fly-ash can have significant effects on the development of mechanical and durability properties of geopolymer concrete when cured at normal temperature. The strength of the geopolymer concretes enhanced from the early age and continued to develop in similar manner as in OPC concrete. Strength increased with the increase of slag in the mixture. The geopolymer concretes showed durability properties comparable to those of the control OPC concrete. In general, the results show that it is possible to design fly ash and slag blended geopolymer concrete suitable for ambient curing with similar or better durability properties of conventional OPC concrete

5. CONCLUSION

5.1. Introduction

This Chapter presents a brief summary of the study and a set of conclusions drawn from the study. Some durability properties of slag blended fly ash-based geopolymer concrete were studied. The durability properties included in the study were drying shrinkage, sorptivity, VPV, sulphate resistance, and resistance to alternate wetting and drying cycles.

Class F fly ash locally available in Western Australia was used to make geopolymer concrete. The alkaline activator was prepared in the laboratory by mixing the sodium hydroxide solution with sodium silicate solution. Other ingredients used in concrete included local coarse and fine aggregates, ground granulated blast furnace slag, water and superplasticiser. The coarse aggregates were crushed granite-type aggregates comprising 20 mm, 14 mm and 7 mm and the fine aggregate was sand.

The mixture proportions used in this study were developed based on a constant total binder content of 400 Kg/m^3. Two different mixtures (series A and B) with 40% and 35% alkaline activator content were used for the geopolymer concrete specimens. Two mixtures with ordinary Portland cement were also used to compare with the results of geopolymer concrete mixtures. The average highest compressive strength of series A was about 55 MPa and that of series B was about 45 MPa.

The mixing for all geopolymer and OPC concrete mixtures were manufactured in the laboratory using the 70-litres pan mixer. Due to the limitation of mixer pan capacity each concrete mixture was prepared in two batches named as Batch-1 and Batch-2. The fly ash and the aggregates were first mixed together in the pan mixer. This was followed by the addition of the activator solutions to the dry materials and the mixing continued for further about 3-5 minutes to produce fresh geopolymer concrete. The fresh concrete was then cast into the moulds in three layers for cylindrical specimens or two layers for other concrete specimens. After

pouring each layer, the moulds were compacted on a vibration table. The geopolymer concrete samples were cured at ambient condition of the laboratory (15-20^{0}C and 60±10% RH) until the test days and the OPC concrete samples were cured under water up to 28 days.

The workability of fresh concrete mixtures was measured by slump test in accordance with the ASTM standard. Cylinder specimens of 100 mm in diameter and 200 mm in height were cast and were used for compressive strength, sorptivity and volume of permeable voids tests. Specimens of 150 × 200 mm cylinders were cast for the split tensile strength test and 100 × 100 × 400mm beams were cast for modulus of rupture and drying shrinkage tests. Specimens for drying shrinkage test were 75×75×285 mm prisms and the drying shrinkage was observed for a period up to 180 days.

The effect of alternate wetting and drying on concrete specimens was studied by using100 × 200 mm cylinders specimens. All specimens of geopolymer concrete were ambient-cured for 28 days and then subjected to alternate immersion in NaCl solution and drying cycles. Two different conditions of drying were used to study the effect of different drying conditions.

For sulphate resistance tests, the test specimens were immersed in 5% sodium sulphate solution for various periods of exposure up to 180 days. Cylinder specimens of dimension 100 mm diameter and 200 mm height were used for changes in compressive strength and mass tests, and prism specimens of 75 mm ×75 mm ×285 mm were used to test the length change for each mixture.

5.2. Conclusions

Based on the test results, the following conclusions are drawn:

- Geopolymer concrete cured in the laboratory ambient condition gained compressive strength with age. Inclusion of slag improved the early-age strength as compared to control fly ash geopolymer concrete. Significant strength development occurred during the period between 28days and 56

days. The addition of extra water and naphthalene based superplasticiser improves the workability of the fresh geopolymer concrete. However, addition of extra water in geopolymer concrete mixtures decreased the compressive strength. The 28-day compressive strength of slag blended fly ash based geopolymer concrete reached 54 MPa using 20% GGBFS with a SS/SH ratio 1.5 which further increased to 70 MPa at 180days.

- The incorporation of slag in the fly ash based geopolymer concrete increased flexure and tensile strengths. Strength at 28 days increased for the 20% replacement of fly ash by GGBFS along with reduced SS/SH ratio. The test results for both flexure and tensile strength values are higher than the values calculated by the equations given in relevant Australian Standard for OPC concrete.

- The drying shrinkage of ambient-cured geopolymer concrete decreased with the increase of slag content up to 20% as replacement of fly ash. Incorporation of GGBFS in the binder of fly ash based geopolymer concrete showed less drying shrinkage than the concrete without GGBFS (series B). Moreover, the values of drying shrinkage for all geopolymer concrete at 56 days were well below than 1000×10^{-6} as specified by AS 1379-2007 (Standard Australia, 2007). On the other hand, geopolymer concrete mixture achieved less drying shrinkage than the OPC concrete of similar strength.

- The incorporation of slag in the binder of geopolymer concrete reduced the sorption at 28 days. Significant reduction of sorption was observed for the inclusion of 20% GGBFS with reduced SS/SH ratio (series A). Effect of additional water on sorption rate indicated similar trend as that of compressive strength (Series B). Moreover, rate of sorption further decreased for all geopolymer concrete after 180 days. When compared with OPC concrete of similar compressive strength, geopolymer concrete has shown less sorptivity.

- The volume of permeable voids (VPV) values of geopolymer concrete decreased with the increase of GGBFS content and reduced SS/SH ratio in the mixtures. In addition, VPV of the concrete samples at 180 days was less than that of the samples cured for 28 days. Generally, VPV decreased with the decrease of alkaline activator from 40% to 35%. However, extra water in the geopolymer mixture (Series B) increased volume of permeable voids of the geopolymer concrete. The geopolymer concrete mixture that achieved similar strength of OPC at 28 days, exhibited a considerably lower value of VPV than the OPC concrete.

- The slag blended fly ash-based geopolymer concrete has good resistance to sulphate attack. The resistance to sulphate attack increased with the increase of slag content in the mixtures. There was no sign of crack or any other damage on the surface of the geopolymer concrete samples after exposure to 5% sodium sulphate solution up to 180 days. There are no significant changes in the mass and the compressive strength of test specimens after 180 days of exposure. The geopolymer concrete showed low expansion property in sulphate solution. Moreover, the results show that the expansion of the geopolymer concrete was much less than the OPC concrete specimens.

- Geopolymer concrete subjected to repetitive cycles of wetting in sodium chloride solution and drying at different temperature conditions showed higher compressive strength increment than the OPC concrete. The rate of strength increment is higher for the oven-dry specimens than the ambient-dry specimens. In addition, weight of the geopolymer concrete specimens remained same over the alternate wet and drying cycles whereas some weight loss was observed in the OPC concrete specimens during the exposure periods.

5.2. Opportunity of geopolymer concrete.

GGBFS blended fly ash based geopolymer concrete exhibited excellent resistance to aggressive environments where the durability of Portland cement concrete may be of concern. This can be particularly applicable in aggressive marine environments or sulphate rich soils. The mechanical properties offered by geopolymer suggest its use in structural applications is beneficial. High-early strength gain is a characteristic of geopolymer concrete when ambient cured. It can be used to produce precast and other pre-stressed concrete building components. The early-age strength gain is a characteristic that can best be exploited in the precast industry where steam curing or heated bed curing is common practice and is used to maximize the rate of production of elements.

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Appendix A Concrete Mix design

Concrete Mix Design (ACI 211.4R-08)

Given Information **OPC1 mixture**

Specified Compressive Strength at 28 days f'_c= 6525 psi (45MPa)

Fine Aggregate Properties

Fine ness Modulus	=	1.97
Relative density (Oven dry)	=	2.595
Absorption	=	0.99 %
Bulk density (BD)	=	105.4 lb./ft^3 (1686.76kg/m^3)

Coarse Aggregate Properties

Relative density (Oven dry)	=	2.728
Absorption	=	0.718 %
Bulk density (BD)	=	99.039 lb./ft^3 (1584.9 kg/m^3)

Cement Property

Relative Density (Sp. Gr.) = 3.15

Step 1 Select Slump and Required Strength

Slump = 4 inch 100mm (Table 6.1)
Required Avg. Strength = (6525+1200) =7725psi =53.27MPa

Step 2 Select Maximum Size of Aggregate

Maximum size of aggregate =0.75 inch =20mm (Table 6.2)

Step 3 Select Optimum Coarse Aggregate Content.

Fractional Volume of OD, CA, VCA =0.66 (Table 6.3)
Mass of Dry CA = (Bulk density of CA * VCA*27)
=1764.87lb/yd^3
= 1046.07kg/m^3

Step 4 Estimate Mixing Water and Air Content

Required Water =279lb/yd^3 =165.36kg/m^3 (Table 6.4)
Air Content = 1.5%
Void content of Fine Aggregate =(1- BD of FA/ (RD of A*62.4))*100

=34.9%

Mixing Water Adjustment = (Void content of FA-35)*8
= -0.72 lb/yd3

Water after Adjustment =278.27 lb/yd3

Step 5 Select w/c ratio

Water to Cementitious Material ratio, w/cm =0.37 (Table 6.5)

Step 6 Calculate Content of Cementitious Materials

Mass of Cementitious Materials = (required water / water cement ratio)

$=754.05 lb/yd^3 = 446.92 kg/m^3$

Step 7 Proportion Basic Mixtures with Cement Only

	ft^3	lb/yd^3	kg/m^3
Cement	3.84	754.05	446.93
CAg	10.37	1764.87	1046.04
FAg	7.92	1282.44	760.10
Water	4.47	279.00	165.36
Air	0.41		

Given Information **OPC2 mixture**

Specified Compressive Strength at 28 days f'_c=4350psi = 30MPa

Fine Aggregate Properties

Fine ness Modulus = 1.97
Relative density (Oven dry) =2.595
Absorption = 0.99 %
Bulk density (BD) =105.4lb./ft^3=1686.76kg/m^3

Coarse Aggregate Properties

Relative density (Oven dry) = 2.728
Absorption = 0.718 %
Bulk density (BD) = 99.039 lb/ft^3= 1584.96kg/m^3

Cement Property

Relative Density (Sp. Gr.) = 3.15

Step 1 Select Slump and Required Strength

Slump = 4 inch = 100mm (Table 6.1)
Required Avg. Strength = (4350+1200) =5750psi =40MPa

Step 2 Select Maximum Size of Aggregate

Maximum size of aggregate =0.75 inch = 20mm (Table 6.2)

Step 3 Select Optimum Coarse Aggregate Content

Fractional Volume of OD, CA, VCA =0.66 (Table 6.3)
Mass of Dry CA = (Bulk density of CA * VCA*27)
=1764.87lb/yd^3 =1046.07kg/m^3

Step 4 Estimate Mixing Water and Air Content

Required Water =340lb/yd^3 =201.5kg/m^3 (Table 6.4)
Air Content = 1.5 %
Void content of Fine Aggregate = (1- BD of FA/ (RD of A*62.4))*100
=34.9%
Mixing Water Adjustment = (Void content of FA-35)*8
= -0.72 lb/yd^3
Water after Adjustment =339.27 lb/yd^3

Step 5 Select w/c ratio

Water to Cementitious Material ratio, w/cm =0.55 (Table 6.5)

Step 6 Calculate Content of Cementitious Materials

Mass of Cementitious Materials = (required water / water cement ratio)

$=618.18 lb/yd^3 = 366.92 kg/m^3$

Step 7 Proportion Basic Mixtures with Cement Only

	ft^3	lb/yd^3	kg/m^3
Cement	3.15	618.18	366.93
CAg	10.37	1764.87	1046.04
FAg	7.63	1236.44	732.10
Water	5.45	340.00	201.52
Air	0.41		

Appendix B Trial mix proportions

Mixtures	Label	Casting Date	Coarse aggregate (kg/m^3)			Sand (kg/m^3)	Fly ash (kg/m^3)	GGBFS (kg/m^3)	Cement (kg/m^3)	NaOH sol (kg/m^3)	Na_2SiO_3 sol (kg/m^3)	Water (kg/m^3)	SP (ml/m^3)
			20mm	10mm	7mm								
GPC1	A40 S10 R2.5	02/05/2012	762.6	167.4	279	651	360	40	-	45.7	114.3	-	-
GPC2	A40 S20 R2.5	09/05/2012	762.6	167.4	279	651	320	80	-	45.7	114.3	-	-
GPC3	A40 S10 R1.5	29/05/2012	762.6	167.4	279	651	360	40	-	64	96	-	-
GPC4	A40 S20 R1.5	01/06/2012	762.6	167.4	279	651	320	80	-	64	96	-	-
GPC5	A35 S00 R2.5	15/06/2012	770.8	169.2	282	658	400	0	-	40	100	-	6
GPC6	A35 S10 R2.5	07/06/2012	767.5	168.4	280.8	655	360	40	-	40	100	8	6
GPC7	A35 S20 R2.5	20/07/2012	767.5	168.4	280.8	655	320	80	-	40	100	8	6
GPC8	A35 S00 R1.5	21/06/2012	770.8	169.2	282	658	400	0	-	56	84	-	6
GPC9	A35 S10 R1.5	29/06/2012	768.3	168.6	281.1	655	360	40	-	56	84	8	6
GPC10	A35 S20 R1.5	27/07/2012	767.5	168.4	280.8	655	320	80	-	56	84	8	6
OPC1	-	02/08/2012	662.8	147.3	243.4	768	-	-	446.93	-	-	165.36	-
OPC2	-	10/08/2012	662.8	147.3	243.4	740	-	-	366.4	-	-	201.65	-

APPENDIX C: Compressive strength test

Compressive strength test: SERIES-A

Mix ID: SERIES A40 R2.5

Mix id (testing date)		A40 S10 R2.5 (GPC1)			A40 S20 R2.5 (GPC2)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
7	1	203.9	26.12	26.87	228.4	29.02	31.31
	2	214.1	27.48		241.4	30.70	
	3	212.6	27.01		269	34.20	
28	1	315.4	40.08	40.38	385.6	48.13	46.63
	2	302.0	38.61		358.2	46.07	
	3	332.2	42.47		355.2	45.68	
56	1	357.4	45.05	44.68	397.3	50.48	50.27
	2	356.6	45.31		409.8	52.49	
	3	348.02	44.05		374.4	48.05	
90	1	391.5	50.05	47.24	430.5	54.59	54.27
	2	368.5	46.55		425.1	54.34	
	3	375	47.94		425.2	54.19	
180	1	389.4	49.78	48.88	456.1	58.07	58.60
	2	383.7	48.85		466.5	59.63	
	3	383.4	48.91		448.5	57.56	

Mix ID: SERIES A40 R1.5

Mix id (testing date)		A40 S10 R1.5 (GPC3)			A40 S20 R1.5 (GPC4)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
7	1	192	24.74	24.84	227.9	29.02	29.0
	2	194	24.95		225.4	28.13	
	3	193	24.82		234.2	29.82	
28	1	325	41.55	42.57	463.2	58.62	54.03
	2	335	43.08		402.0	51.39	
	3	337	43.08		407.4	52.08	
56	1	395	49.89	49.78	470.0	60.12	62.81
	2	389	48.94		480.2	61.84	
	3	392	50.62		495.0	63.79	
90	1	405	51.98	52.17	525.0	67.52	67.88
	2	415	52.63		545.0	68.84	
	3	411	51.71		534.0	66.92	
180	1	435	55.72	54.37	550.0	70.73	69.82
	2	425	54.22		540.0	69.03	
	3	429	54.51		560.1	70.61	

Compressive strength test: SERIES-B

Mix ID: SERIES A35 R2.5

Mix id (testing date)		A35 S00 R2.5 (GPC5)			A35 S10 R2.5 (GPC6)			A35 S20 R2.5 (GPC7)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
7	1	72.7	9.33	11.4	116.4	14.79	14.5	174.6	22.50	22.1
	2	101.8	13.01		114.6	14.71		163.3	20.83	
	3	92.6	11.79		109.3	13.97		180.3	22.91	
28	1	198.2	25.34	25.00	205	26.05	27.0	262.2	32.79	34.7
	2	190.2	24.31		210	26.68		278.5	34.97	
	3	197.5	25.35		218	28.09		283.2	36.35	
56	1	231.4	29.58	29.5	245.5	31.32	34.9	312	40.29	39.7
	2	234.1	30.05		268.9	34.44		314	39.35	
	3	226.8	28.99		275.9	35.41		318	39.93	
90	1	247.5	31.58	32.9	285	36.14	37.6	314.1	40.15	42.7
	2	261.7	33.72		289	37.24		333.9	42.68	
	3	251.1	32.10		296.5	38.06		333.9	42.68	
180	1	271.9	34.76	34.6	300.1	38.13	39.1	348.7	44.40	44.3
	2	268.3	34.37		315.1	39.96		341.3	43.63	
	3	273.5	34.89		299.3	38.26		352.3	45.31	

Mix ID: SERIES A35 R1.5

Mix id (testing date)		A35 S00 R1.5 (GPC8)			A35 S10 R1.5(GPC9)			A35 S20 R1.5(GPC10)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
7	1	70	8.88	8.3	109	13.85	14.25	192.5	24.66	25.1
	2	64.3	8.15		116	14.71		193.8	25.02	
	3	60.1	7.67		112.2	14.14		202.6	25.54	
28	1	202.7	25.96	27.4	210.7	26.93	27.00	387.7	49.76	45.4
	2	222.3	28.65		209.2	26.64		342	43.63	
	3	214.1	27.42		214.8	27.51		335.3	43.04	
56	1	237.7	29.85	32.0	281.5	36.06	34.80	401.5	51.02	52.4
	2	254	32.73		273.3	34.25		411.2	52.25	
	3	243.4	31.30		275.4	35.35		410.8	52.41	
90	1	265.5	34.15	33.8	303.1	38.77	40.9	380.3	48.91	54.2
	2	273.5	34.75		320.1	41.33		429.3	54.77	
	3	259.5	32.91		318.1	40.42		421.4	53.65	
180	1	291.4	37.40	36.9	348.5	44.82	44.4	445.5	56.95	57.0
	2	287.6	35.97		355.5	45.17		450.2	57.78	
	3	301.9	37.83		340.5	43.53		437.1	56.21	

Compressive strength test: SERIES-OPC

Mix id (testing date)		OPC1			OPC2		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
7	1	275	35.30	36.0	181.5	22.83	22.8
	2	289	36.94		184.3	23.42	
	3	284	35.73		175.6	22.09	
28	1	378	48.32	48.0	255.5	32.99	32.7
	2	375	48.13		257.8	33.29	
	3	369	47.46		253.5	31.89	
56	1	450	57.64	56.45	285.5	36.28	36.8
	2	445	56.43		289.5	37.08	
	3	438	56.44		282.3	36.38	
90	1	471.6	60.41	62.33	328.1	41.86	39.8
	2	492.1	62.66		289.8	37.88	
	3	485.1	62.01		327.1	41.65	
180	1	509.8	64.91	65.34	340.2	43.4	43.4
	2	520.1	66.62		338.34	44.22	
	3	500.1	64.06		335	42.65	

APPENDIX D: Indirect tensile strength test

Indirect tensile strength test: SERIES-A

Mix ID: GPC1 (A40 S10 R2.5) Casting date: 02/05/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150.0	300.1	165.8	2.40	2.36
	2	150.1	299.8	155.7	2.30	
28	1	150.0	300.0	212.5	3.01	3.09
	2	150.0	300.0	223.7	3.16	
90	1	150.1	300.2	241.0	3.40	3.43
	2	149.8	300.1	244.4	3.46	

Mix ID: GPC2 (A40 S20 R2.5) Casting date: 09/05/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150.0	299.5	180.5	2.56	2.48
	2	149.8	300.1	169.5	2.40	
28	1	149.5	301.0	232.5	3.29	3.25
	2	149.5	301.0	227.2	3.21	
90	1	149.7	300.2	277.0	3.92	3.50
	2	150.1	298.0	215.5	3.07	

Mix ID: GPC3 (A40 S10 R1.5) Casting date: 29/05/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	149.0	300.0	120.5	1.72	1.73
	2	150.0	301.0	123.3	1.74	
28	1	150.1	300.2	206.9	2.92	2.88
	2	149.9	300.5	200.6	2.84	
90	1	150.1	300.2	235.5	3.33	3.73
	2	150.0	300.0	291.5	4.12	

Mix ID: GPC4 (A40 S20 R1.5) Casting date: 01/06/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150	300.0	179.8	2.54	2.74
	2	150	300.0	206.9	2.93	
28	1	150	300.1	322.0	4.55	4.81
	2	150	300.5	358.6	5.06	
90	1	151	301.0	405.0	5.67	5.63
	2	150	300.0	395.0	5.59	

Indirect tensile strength test: SERIES-B

Mix ID: GPC5 (A35 S00 R2.5) Casting date: 15/06/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150	300	106.1	1.50	1.35
	2	150	300	86	1.20	
28	1	150	300	151	2.14	2.12
	2	150	300	149	2.11	
90	1	149.5	300	185.6	2.63	2.60
	2	150.3	301	182.9	2.57	

Mix ID: GPC6 (A35 S10 R2.5) Casting date: 07/06/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150	300	102.3	1.45	1.43
	2	150	300	100.5	1.42	
28	1	150.1	300.2	198.5	2.80	2.68
	2	150.2	299.8	180.5	2.55	
90	1	149.8	300	210.9	2.99	2.98
	2	150.5	301	211.2	2.97	

Mix ID: GPC7 (A35 S20 R2.5) Casting date: 20/07/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150	300	102.3	1.45	1.43
	2	150	300	100.5	1.42	
28	1	149.8	300	208.3	2.95	3.02
	2	150	300	218	3.08	
90	1	150.1	300	235.5	3.33	3.28
	2	149.5	301	228.5	3.23	

Mix ID: GPC8 (A35 S00 R1.5) Casting date: 21/06/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	148	295	61.4	0.90	1.00
	2	147	302	77	1.10	
28	1	150	299.8	153.5	2.17	2.27
	2	150	298.8	166.9	2.37	
90	1	149.5	299.5	188.1	2.67	2.98
	2	150	301	233	3.29	

Mix ID: GPC9 (A35 S10 R1.5) Casting date: 29/06/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150.1	299.8	75.1	1.06	1.25
	2	150	300	102.2	1.45	
28	1	150	300	215.5	3.05	3.03
	2	150	300	212.3	3.00	
90	1	150	301	241.1	3.40	3.67
	2	149.8	300	278	3.94	

Mix ID: GPC10 (A35 S20 R1.5) Casting date: 27/07/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150.1	299.8	151.1	2.14	2.14
	-	-	-	-	-	
28	1	150	300	262.7	3.72	3.75
	2	150	300	266.8	3.77	
90	1	150	300	289.1	4.09	4.10
	2	149.7	299.8	290.3	4.12	

Indirect tensile strength test: SERIES-OPC

Mix ID: OPC1 Casting date: 02/08/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150.1	299.8	218.1	3.09	3.23
	2	150	300	238	3.37	
28	1	150	300	291.8	4.13	4.15
	2	150	300	295.6	4.18	
90	1	150	300	300.4	4.25	4.26
	2	150	300	302.2	4.28	

Mix ID: OPC2 Casting date: 10/08/2012

Days	Sample no	Diameter (mm)	Height (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	150	300.2	224.5	3.17	3.17
	2	150	300	223.1	3.16	
28	1	150.2	301	249	3.51	3.43
	2	149.8	299.5	236.2	3.35	
90	1	149.7	300	250.1	3.55	3.64
	2	149.8	299.8	262.8	3.73	

APPENDIX F: Flexural strength test (Modulus of rupture)

Flexural strength test: SERIES-A

Mix ID: GPC1 (A40 S10 R2.5) Casting date: 02/05/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	100.1	100.5	300	10.85	3.219	3.2
	2	100.1	100.4	300	10.5	3.122	
28	1	100	100.45	300	15.53	4.617	4.7
	2	100.2	100.15	300	15.91	4.749	
90	1	100.5	105	300	18.36	4.971	4.9
	2	99	104.5	300	17.66	4.901	

Mix ID: GPC2 (A40 S20 R2.5) Casting date: 09/05/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	100.2	100.5	300	10.55	3.127	3.1
	2	100.1	100.4	300	10	2.973	
28	1	100	100.45	300	15.96	4.745	4.9
	2	100.2	100.15	300	17.09	5.101	
90	1	104	102	300	21.19	5.875	5.3
	2	102.45	103.5	300	17.03	4.655	

Mix ID: GPC3 (A40 S10 R1.5) Casting date: 29/05/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	100	100.45	300	10.31	3.065	3.048
	2	100.2	100.15	300	10.15	3.030	
28	1	102	98.5	300	16.11	4.884	5.0
	2	103	100.85	300	17.79	5.095	
90	1	100.5	102.5	300	18.45	5.242	5.44
	2	100.2	100.15	300	18.9	5.642	

Mix ID: GPC4 (A40 S20 R1.5) Casting date: 01/06/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	101.5	100.45	300	13.04	3.820	4.0
	2	100.2	100.15	300	13.85	4.134	
28	1	106.5	101.5	300	19.05	5.209	5.15
	2	105.5	104.5	300	19.45	5.065	
90	1	100	102.5	300	20.15	5.754	5.62
	2	105	102.5	300	20.05	5.453	

Flexural strength test: SERIES-B

Mix ID: GPC5 (A35 S00 R2.5) Casting date: 15/06/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	102.5	98.5	300	9.01	2.718	2.68
	2	100.5	101	300	8.98	2.628	
28	1	101.5	100.5	300	14.68	4.296	4.1
	2	103	104.5	300	14.45	3.854	
90	1	104.5	102.5	300	15.85	4.331	4.3
	2	102.5	105.5	300	16.15	4.247	

Mix ID: GPC6 (A35 S10 R2.5) Casting date: 07/06/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	105.5	100.05	300	10.38	2.949	3.2
	2	100.2	100.15	300	11.4	3.403	
28	1	104.5	100.5	300	13.57	3.857	3.85
	2	103.5	101.5	300	13.64	3.838	
90	1	100.5	104.5	300	16.75	4.579	4.65
	2	99.5	103.5	300	16.83	4.737	

Mix ID: GPC7 (A35 S20 R2.5) Casting date: 20/07/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	104.5	99.95	300	10.4	2.989	3.1
	2	99.5	100	300	10.23	3.084	
28	1	102.5	104	300	15.52	4.200	4.22
	2	102.5	105.5	300	16.13	4.242	
90	1	105.5	102	300	17.95	4.906	4.9
	2	105	103	300	18.18	4.896	

Mix ID: GPC8 (A35 S00 R1.5) Casting date: 21/06/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	104	100.5	300	6.84	1.953	1.88
	2	103	104.5	300	6.71	1.790	
28	1	105.5	102.5	300	13.32	3.605	3.68
	2	105.5	103.5	300	14.07	3.735	
90	1	102.5	105.5	300	17.84	4.691	4.5
	2	103.5	106.5	300	16.95	4.332	

Mix ID: GPC9 (A35 S10 R1.5) Casting date: 29/06/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	102.5	102.5	300	9.14	2.546	2.47
	2	101	102.5	300	8.43	2.383	
28	1	102	98.5	300	14.05	4.259	4.15
	2	103	100.85	300	14.13	4.046	
90	1	101	102.5	300	17.25	4.877	4.91
	2	101.5	102	300	17.37	4.935	

Mix ID: GPC10 (A35 S20 R1.5) Casting date: 27/07/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	102.5	102.5	300	10.25	2.855	2.85
	2	101	102.5	300	10.19	2.881	
28	1	102	98.5	300	14.25	4.320	4.28
	2	103	100.85	300	14.78	4.233	
90	1	101	102.5	300	18.43	5.210	5.16
	2	101.5	102	300	18.09	5.139	

Indirect tensile strength test: SERIES-OPC

Mix ID: OPC1 Casting date: 02/08/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	103	102.5	300	16.92	4.691	4.7
	2	101.5	300	16.53	4.719	101.5	
28	1	101.5	100.5	300	17.35	5.077	4.98
	2	102.5	101.5	300	17.15	4.872	
90	1	99.5	103.5	300	18.48	5.201	5.27
	2	99.5	101.5	300	18.22	5.332	

Mix ID: OPC2 Casting date: 10/08/2012

Days	Sample no	Avg. B (mm)	Avg. D (mm)	Span, L (mm)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
7	1	102	101	300	12.25	3.532	3.54
	2	101	102.5	300	12.53	3.542	
28	1	101.5	102	300	15.54	4.415	4.15
	2	102.5	102	300	13.76	3.871	
90	1	101.5	100	300	16.73	4.945	4.75
	2	101.5	99.5	300	15.19	4.535	

APPENDIX G: Volume of permeable void test.

Volume of permeable void test: SERIES-A

Mix ID: GPC1 (A40 S10 R2.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	873.98	908.49	913.48	540.92	3.95	4.52	10.60
2	845.91	882.95	887.59	524.73	4.38	4.93	11.49
3	845.13	880.27	884.62	525.16	4.16	4.67	10.99
4	908.42	943.69	947.7	567.06	3.88	4.32	10.32
Avg					4.09	4.61	10.88

Mix ID: GPC1 (A40 S10 R2.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	931.09	967.1	971.36	578.64	3.87	4.33	10.25
2	844.06	877.88	881.94	523.53	4.01	4.49	10.57
3	873.83	912.01	915.91	542.68	4.37	4.82	11.27
4	900.47	936.86	941.48	559.53	4.04	4.55	10.74
Avg					4.07	4.55	10.71

Mix ID: GPC2 (A40 S20 R2.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	888.59	921.58	926.16	552.5	3.71	4.23	10.05
2	954.95	990.95	996.16	596.4	3.77	4.32	10.31
3	781.96	813.64	817.89	485.31	4.05	4.59	10.80
4	834.99	871.33	877.83	516.24	4.35	5.13	11.85
Avg					3.97	4.57	10.75

Mix ID: GPC2 (A40 S20 R2.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	886.16	920.61	923.14	550.55	3.89	4.17	9.93
2	836.53	872.43	875.42	520.03	4.29	4.65	10.94
3	850.01	885.3	888.25	528.76	4.15	4.50	10.64
4	940.15	981.88	985.28	581.66	4.44	4.80	11.18
Avg					4.19	4.53	10.67

Mix ID: GPC3 (A40 S10 R1.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	998.29	1035.29	1041.13	575.24	3.71	4.29	998.29
2	859.07	893.35	897.38	543.23	3.99	4.46	859.07
3	849.98	883.16	889.61	533.29	3.90	4.66	849.98
4	827.35	859.28	866.15	506.27	3.86	4.69	827.35
Avg					3.86	4.53	10.48

Mix ID: GPC3 (A40 S10 R1.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	933.41	971.4	974.88	582.35	4.07	4.44	10.56
2	876.71	909.5	915.5	545.42	3.74	4.42	10.48
3	832.59	860.5	866.4	515.27	3.35	4.06	9.63
Avg					3.72	4.31	10.23

Mix ID: GPC4 (A40 S20 R1.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	880.67	914.25	923.52	525.25	3.81	4.87	10.76
2	808.78	842.63	850.24	457.8	4.19	5.13	10.56
3	846.29	882.45	889.62	491.5	4.27	5.12	10.88
4	863.24	889.28	898.25	506.25	3.02	4.06	8.93
Avg					3.82	4.79	10.28

Mix ID: GPC4 (A40 S20 R1.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	900.71	929.05	934.18	555.68	3.15	3.72	8.84
2	872.53	900.24	904.79	536.03	3.18	3.70	8.75
3	836.04	862.72	876.95	514.79	3.19	4.89	11.30
4	980.55	1008.81	1014.13	603.86	2.88	3.42	8.18
Avg					3.10	3.93	9.27

Volume of permeable void test: SERIES-B

Mix ID: GPC5 (A35 S00 R2.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	886.31	918.44	928.37	550.53	3.63	4.75	11.13
2	824.69	857.5	864.96	511.69	3.98	4.88	11.40
3	841.89	878.54	884.9	520.13	4.35	5.11	11.79
4	852.55	888.64	893.72	526.31	4.23	4.83	11.21
Avg					4.05	4.89	11.38

Mix ID: GPC5 (A35 S00 R2.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	915.5	953.22	960.15	568.25	4.12	4.88	11.39
2	842.5	877.99	884.47	521.06	4.21	4.98	11.55
3	828.7	862.07	868.04	514.02	4.03	4.75	11.11
4	889.44	921.96	927.44	549	3.66	4.27	10.04
Avg					4.00	4.72	11.02

Mix ID: GPC6 (A35 S10 R2.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	890.73	925.43	932.27	551	3.90	4.66	10.90
2	868.93	906.06	910.12	539.57	4.27	4.74	11.12
3	-	-	-	-	-	-	-
4	882.5	920.47	925.5	544.37	4.30	4.87	11.28
Avg					4.16	4.76	11.10

Mix ID: GPC6 (A35 S10 R2.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	898.7	931.31	936.08	556.23	3.63	4.16	9.84
2	829.5	866.64	871.09	530.31	4.48	5.01	12.20
3	859.8	896.32	900.32	513.02	4.25	4.71	10.46
4	860.95	897.74	902.93	528.34	4.27	4.88	11.21
Avg					4.16	4.69	10.93

Mix ID: GPC7 (A35 S20 R2.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	889.06	923.94	930.68	540.13	3.92	4.68	10.66
2	859.05	894.94	901.92	524.14	4.18	4.99	11.35
3	872.89	908.87	915.09	530.05	4.12	4.83	10.96
4	809.63	840.36	846.07	496.633	3.80	4.50	10.43
Avg					4.00	4.75	10.85

Mix ID: GPC7 (A35 S20 R2.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	891.8	921.66	929.4	549.67	3.35	4.22	9.90
2	843	872.39	880.92	515.03	3.49	4.50	10.36
3	841.9	871.48	880.67	514.12	3.51	4.61	10.58
4	842.04	879.44	887.59	516.65	4.44	5.41	12.28
Avg					3.70	4.68	10.78

Mix ID: GPC8 (A35 S00 R1.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	880.51	913.99	921.12	538.48	3.80	4.61	10.61
2	800.03	833.32	838.92	490.43	4.16	4.86	11.16
3	837.18	873.59	878.92	509.35	4.35	4.99	11.29
4	837.57	874.15	880.76	507.14	4.37	5.16	11.56
Avg					4.17	4.90	11.16

Mix ID: GPC8 (A35 S00 R1.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	849.9	886.81	892.51	515.64	4.34	5.01	11.31
2	838.61	873.01	878.06	509.4	4.10	4.70	10.70
3	822.48	856.86	863.25	497.75	4.18	4.96	11.15
4	863.29	897.02	904.03	521.58	3.91	4.72	10.65
Avg					4.13	4.85	10.95

Mix ID: GPC9 (A35 S10 R1.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	911.25	955.26	963.1	517.85	4.83	5.69	11.65
2	848.23	879.25	885.63	516.25	3.66	4.41	10.13
3	830.25	861.25	869.31	505.53	3.73	4.70	10.74
4	851.12	885.29	892.35	518.22	4.01	4.84	11.02
Avg					4.06	4.91	10.88

Mix ID: GPC9 (A35 S10 R1.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	882.5	910.82	918.51	515.64	3.21	4.08	8.94
2	797.5	828.22	836.06	509.4	3.85	4.84	11.80
3	829.6	864.55	872.25	497.75	4.21	5.14	11.39
4	842.67	876.45	884.03	501.2	4.01	4.91	10.80
Avg					3.82	4.74	10.73

Mix ID: GPC10 (A35 S20 R1.5) **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	911.02	945.7	952.54	563.34	3.81	4.56	10.67
2	880.14	915.88	922.48	541.74	4.06	4.81	11.12
3	823.14	858.94	864.91	505.19	4.35	5.07	11.61
4	856.12	884.07	890.97	515.37	3.26	4.07	9.28
Avg					3.87	4.63	10.67

Mix ID: GPC10 (A35 S20 R1.5) **Curing tenure: 180 days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	825.9	856.62	861.13	509.02	3.72	4.27	10.01
2	837.91	870.45	874.81	516.09	3.88	4.40	10.29
3	855.98	893.06	898.04	522.92	4.33	4.91	11.21
4	914.48	953.43	957.14	555.15	4.26	4.66	10.61
Avg					4.05	4.56	10.53

Volume of permeable void test: SERIES-OPC

Mix ID: OPC1 **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	919.24	969.02	970.31	571.48	5.42	5.56	12.80
2	822.14	870.37	871.47	510.77	5.87	6.00	13.68
3	844.58	895.9	896.94	523.14	6.08	6.20	14.01
4	795.7	844.55	845.61	492.94	6.14	6.27	14.15
Avg					5.87	6.01	13.66

Mix ID: OPC1 **Curing tenure: 180days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	850.41	898.59	898.81	532.38	5.67	5.69	13.21
2	854	906.58	906.31	535.14	6.16	6.13	14.09
3	848.42	898.96	898.45	527.74	5.96	5.90	13.50
4	862.9	910.32	911.85	525.37	5.50	5.67	12.67
Avg					5.82	5.85	13.37

Mix ID: OPC2 **Curing tenure: 28days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	820.25	875	876.1	482.1	6.67	6.81	14.18
2	817.88	868	869.2	477.2	6.13	6.27	13.09
3	833.41	895	896.1	499.6	7.39	7.52	15.81
4	862.93	910	911.2	508.5	5.45	5.59	11.99
Avg					6.41	6.55	13.77

Mix ID: OPC2 **Curing tenure: 180days**

sample No	Oven dry wt. M_1 (gm)	SSD wt. M_{2i} (gm)	Boiled wt. M_{3b} (gm)	Submerged wt. M_{4ib} (gm)	Immersed Absorption (%)	Boiled Absorption (%)	VPV (%)
1	838.9	878.75	878.51	515.74	4.75	4.72	10.92
2	811.95	860.38	860.52	501.03	5.96	5.98	13.51
3	835.98	892.36	891.91	511.52	6.74	6.69	14.70
4	877.95	937.32	937.32	537.02	6.76	6.76	14.83
Avg					6.06	6.04	13.49

APPENDIX H: Drying shrinkage test
Drying shrinkage test: SERIES-A

Mix ID: GPC1 (A40 S10 R2.5) Casting date: 02/05/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.0045	0.0026	-0.0084	-	-	-	-
14	-0.042	-0.13	-0.15	147.3	541.1	553.1	413.82
21	-0.08	-0.162	-0.164	300.7	658.4	621.1	526.71
28	311.34	658.4	637.1	-0.0824	-0.162	-0.168	535.60
56	314	670.4	626.4	-0.083	-0.165	-0.165	536.94
90	352.67	670.40	641.07	-0.0927	-0.165	-0.169	554.71
120	342.0	693.1	674.4	-0.09	-0.171	-0.177	569.83
180	371.4	735.8	709.1	-0.0973	-0.1813	-0.185	605.40

Mix ID: GPC2 (A40 S20 R2.5) Casting date: 09/05/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.105	-0.1848	0.0888	-	-	-	-
14	-0.204	-0.196	-0.037	394.67	43.47	501.87	313.33
21	-0.227	-0.207	-0.055	489.33	87.47	573.87	383.55
28	-0.235	-0.212	-0.069	521.33	107.47	629.87	419.55
56	-0.245	-0.218	-0.068	560.00	131.47	625.87	439.11
90	-0.257	-0.222	-0.065	606.67	150.13	616.53	457.77
120	-0.261	-0.226	-0.071	624.00	164.80	640.53	476.44
180	-0.273	-0.224	-0.081	672.00	155.47	677.87	501.77

Mix ID: GPC3 (A40 S10 R1.5) Casting date: 29/05/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.415	0.387	-0.0964	-	-	-	-
14	0.401	0.297	-0.203	57.6	360.27	426.40	281.43
21	0.385	0.293	-0.228	120.27	377.60	526.40	341.43
28	0.371	0.257	-0.253	177.60	521.60	626.40	441.87
56	0.365	0.241	-0.266	201.60	585.60	677.07	488.10
90	0.353	0.242	-0.264	248.27	582.93	669.07	500.10
120	0.343	0.240	-0.273	288.27	590.93	705.07	528.10
180	0.339	0.237	-0.276	305.60	602.93	717.07	541.90

Mix ID: GPC4 (A40 S20 R1.5) Casting date: 01/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.158	-0.027	-0.349	-	-	-	-
14	-0.186	-0.053	-0.393	112.27	105.07	175.73	131.02
21	-0.2	-0.098	-0.425	165.60	282.40	303.73	250.58
28	-0.23	-0.098	-0.434	285.60	283.73	339.73	303.02
56	-0.252	-0.123	-0.453	374.93	383.73	415.73	391.47
90	-0.256	-0.126	-0.461	392.27	395.73	446.40	411.47
120	-0.259	-0.126	-0.462	404.27	395.73	450.40	416.80
180	-0.275	-0.140	-0.477	466.93	451.73	513.07	477.24

Drying shrinkage test: SERIES-B

Mix ID: GPC5 (A35 S00 R2.5) Casting date: 15/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.0442	-0.37	0.0054	-	-	-	-
14	-0.227	-0.468	-0.092	729.87	393.33	388.27	503.82
21	-0.242	-0.476	-0.102	789.87	424.00	428.27	547.38
28	-0.257	-0.483	-0.105	851.20	453.33	440.27	581.60
56	-0.268	-0.488	-0.108	893.87	470.67	452.27	606.60
90	-0.325	-0.492	-0.116	1124.53	486.67	485.60	698.90
120	-0.365	-0.486	-0.122	1281.87	465.33	508.27	751.80
180	-0.425	-0.485	-0.110	1521.87	458.67	462.93	814.48

Mix ID: GPC6 (A35 S10 R2.5) Casting date: 07/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.195	-0.026	0.601	-	-	-	-
14	-0.227	-0.136	0.438	128.267	438.667	650.667	405.87
21	-0.229	-0.146	0.429	136.267	478.667	689.333	434.76
28	-0.231	-0.154	0.416	144.267	513.333	738.667	465.42
56	-0.240	-0.163	0.413	180.267	549.333	750.667	493.42
90	-0.244	-0.175	0.401	196.267	597.333	798.667	530.75
120	-0.285	-0.178	0.400	361.600	609.333	805.333	592.08
180	-0.350	-0.180	0.396	621.600	617.333	818.667	685.87

Mix ID: GPC7 (A35 S20 R2.5) Casting date: 20/07/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.0552	-0.0304	-0.0738	-	-	-	-
14	-0.0583	-0.0903	-0.1360	12.53	239.73	248.80	167.02
21	-0.0753	-0.1160	-0.1637	80.53	342.40	359.47	260.8
28	-0.0790	-0.1270	-0.1713	95.20	386.40	390.13	290.58
56	-0.0957	-0.1520	-0.1803	161.87	486.40	426.13	358.13
90	-0.0950	-0.2200	-0.1903	159.20	758.40	466.13	491.25
120	-0.0957	-0.2200	-0.2207	161.87	758.40	587.47	502.58
180	-0.0977	-0.2300	-0.2277	169.87	798.40	615.47	527.9

Mix ID: GPC8 (A35 S00 R1.5) Casting date: 21/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.4829	0.0978	-0.0072	-	-	-	-
14	0.405	-0.136	-0.216	312.53	935.20	833.87	693.87
21	0.402	-0.147	-0.218	321.87	977.87	841.87	713.87
28	0.395	-0.148	-0.219	349.87	981.87	848.53	726.76
56	0.385	-0.146	-0.224	391.20	976.53	868.53	745.43
90	0.374	-0.149	-0.224	436.53	987.20	867.20	763.64
120	0.357	-0.151	-0.212	503.20	995.20	819.20	772.53
180	0.336	-0.153	-0.212	585.87	1001.87	819.20	802.31

Mix ID: GPC9 (A35 S10 R1.5) Casting date: 29/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.125	-0.1152	-0.1732	-	-	-	-
14	-0.197	-0.207	-0.320	284.27	367.20	585.87	412.45
21	-0.221	-0.225	-0.335	381.60	440.53	645.87	489.33
28	-0.226	-0.237	-0.345	401.60	487.20	687.20	525.33
56	-0.244	-0.261	-0.365	472.27	581.87	767.20	607.11
90	-0.252	-0.267	-0.369	505.60	605.87	784.53	632.00
120	-0.251	-0.267	-0.372	500.27	605.87	796.53	634.22
180	-0.254	-0.269	-0.375	512.27	613.87	807.20	644.44

Mix ID: GPC10 (A35 S20 R1.5) Casting date: 27/07/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.3062	-0.0492	-0.8774	-	-	-	-
14	0.263	-0.106	-0.930	172.80	225.87	209.07	202.58
21	0.258	-0.115	-0.962	191.47	264.53	339.73	265.25
28	0.255	-0.126	-0.990	206.13	305.87	449.07	320.36
56	0.210	-0.170	-1.001	383.47	481.87	495.73	453.69
90	0.195	-0.172	-1.002	446.13	489.87	499.73	478.58
120	0.180	-0.177	-1.006	504.80	509.87	515.73	510.13
180	0.172	-0.177	-1.006	535.47	509.87	515.73	520.36

Drying shrinkage test: SERIES-OPC

Mix ID: OPC1 Casting date: 02/08/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.003	-0.089	0.0626	-	-	-	-
14	-0.062	-0.154	-0.003	260.00	258.67	262.40	260.36
21	-0.080	-0.168	-0.014	332.00	317.33	305.07	318.14
28	-0.087	-0.178	-0.018	360.00	357.33	322.40	346.58
56	-0.120	-0.211	-0.052	493.33	488.00	459.73	480.36
90	-0.127	-0.218	-0.062	520.00	516.00	499.73	511.92
120	-0.133	-0.214	-0.070	542.67	498.67	531.73	524.36
180	-0.143	-0.229	-0.075	584.00	560.00	549.07	564.36

Mix ID: OPC2 Casting date: 10/08/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.2246	-0.0154	-0.204	-	-	-	-
14	-0.294	-0.079	-0.273	277.60	255.73	277.33	270.23
21	-0.303	-0.087	-0.286	313.60	285.07	328.00	308.89
28	-0.329	-0.105	-0.306	416.27	358.40	409.33	394.67
56	-0.343	-0.124	-0.326	472.27	435.73	488.00	465.33
90	-0.369	-0.146	-0.350	578.93	523.73	582.67	561.78
120	-0.384	-0.163	-0.357	637.60	591.73	610.67	613.33
180	-0.389	-0.165	-0.359	657.60	598.40	620.00	625.33

APPENDIX I: TEST FOR SULPHATE ATTACK.

Compressive strength test: SERIES-A (sulphate solution)

Mix ID: SERIES A40 R2.5

Mix id		A40 S10 R2.5 (GPC1)			A40 S10 R1.5 (GPC3)			A40 S20 R1.5 (GPC4)		
Days	**No**	**Load (KN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (KN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (KN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	379.6	48.72		395	50.49		495.5	62.71	
	2	356.1	45.89	47.3	397.5	50.92	50.71	505.5	64.88	63.8
90	1	418.5	52.76		420	53.37		540.5	69.09	
	2	411.5	52.18	52.4	415	53.48	53.42	529.5	68.23	68.6
180	1	421.1	53.83		416.2	53.53		565.5	72.44	
	2	408.5	52.12	53.0	453.5	58.09	55.81	557.5	71.55	72.0

Compressive strength test: SERIES-B

Mix id		A35 S00 R2.5 (GPC5)			A35 S10 R2.5 (GPC6)		
Days	**No**	**Load (KN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (KN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	239.8	30.72		285.5	36.06	
	2	227	29.14	29.9	287.5	36.90	36.5
90	1	262.5	33.76		305.5	38.51	
	2	269.5	34.59	34.1	300.2	38.45	38.5
180	1	286	36.63		325.5	41.61	
	2	279.1	35.54	36.1	315.5	40.09	40.8

Mix id		A35 S20 R2.5 (GPC7)			A35 S10 R1.5 (GPC9)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	321	40.79		273.5	34.48	
	2	347.3	44.04	42.4	286	36.78	35.6
90	1	429.8	55.39		325.6	41.37	
	2	389.5	50.19	52.8	323.2	41.32	41.4
180	1	444.3	57.14		310.51	40.01	
	2	423.5	54.14	55.6	395.7	50.28	45.1

Compressive strength test: SERIES- OPC

Mix id		OPC1			OPC2		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	478	60.74		300.5	38.18	
	2	463.9	58.83	59.8	315.5	40.41	39.3
90	1	483.5	61.56		309.5	39.41	
	2	351.5	45.02	60.9	302.2	38.55	38.9
180	1	328.5	41.99		200.5	25.68	
	2	452.9	57.90	43.0	206.5	26.50	26.1

Length change test: SERIES-A

Mix ID: GPC1 (A40 S10 R2.5) Casting date: 02/05/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.091	-0.1086	0.1826	-	-	-	-
14	-0.093	-0.121	0.182	6.67	49.60	2.40	19.56
21	-0.084	-0.107	0.183	-26.67	-5.07	-2.93	-11.56
28	-0.085	-0.105	0.188	-24.00	-14.40	-20.27	-19.56
56	-0.082	-0.101	0.189	-34.67	-31.73	-24.27	-30.23
90	-0.077	-0.103	0.191	-57.333	-21.067	-32.267	-36.889
120	-0.073	-0.100	0.191	-72.000	-33.067	-32.267	-45.778
180	-0.070	-0.099	0.189	-85.333	-37.067	-24.267	-48.889

Mix ID: GPC3 (A40 S10 R1.5) Casting date: 29/05/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.07828	-0.0126	0.1582	-	-	-	-
14	-0.070	-0.009	0.158	-11.20	-14.40	-0.40	-8.67
21	-0.069	-0.010	0.158	-16.53	-12.40	-0.53	-9.83
28	-0.068	-0.009	0.158	-20.53	-12.53	-0.93	-10.97
56	-0.068	-0.010	0.159	-20.53	-11.73	-1.33	-11.20
90	-0.06	-0.01	0.16	-35.20	-11.07	-1.73	-16.00
120	-0.0620	-0.0063	0.1587	-43.20	-25.33	-2.13	-23.55
180	-0.061	0.001	0.1588	-47.2	-54.4	-2.4	-34.66

Mix ID: GPC4 (A40 S20 R1.5) Casting date: 01/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.023	-0.0186	-0.0486	-	-	-	-
14	0.019	-0.035	-0.059	14.667	66.933	40.267	40.62
21	0.013	-0.031	-0.053	41.333	49.600	16.267	35.73
28	0.014	-0.029	-0.055	36.000	41.600	24.267	33.96
56	0.011	-0.011	-0.043	46.667	-31.733	-22.400	-2.48
90	0.009	-0.006	-0.037	57.333	-49.067	-46.400	-12.71
120	0.0057	-0.0070	-0.0280	69.333	-46.400	-82.400	-19.82
180	0.002	-0.004	-0.022	82.667	-58.400	-106.400	-27.37

Length change test: SERIES-B

Mix ID: GPC5 (A35 S00 R2.5) Casting date: 15/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.003	0.121	0.082	-	-	-	-
14	-0.0016	0.1273	0.07	-6.933	-24.533	47.200	5.244
21	0.001	0.127	0.072	-17.600	-23.200	39.200	-0.533
28	0.005	0.128	0.078	-33.600	-27.200	15.200	-15.20
56	0.0063	0.1296	0.08	-38.933	-33.867	7.200	-21.87
90	0.008	0.135	0.082	-45.600	-55.200	-0.800	-33.86
120	0.0085	0.14	0.0836	-47.600	-75.200	-7.467	-43.42
180	0.009	0.145	0.086	-49.600	-95.200	-16.800	-53.87

Mix ID: GPC6 (A35 S10 R2.5) Casting date: 07/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.0348	0.58	0.296	-	-	-	-
14	-0.0500	0.5540	0.2957	60.80	104.00	2.93	55.91
21	-0.0473	0.5607	0.2997	50.13	77.33	-13.07	38.13
28	-0.0457	0.5707	0.3010	43.47	37.33	-18.40	20.80
56	-0.0447	0.5697	0.3067	39.47	41.33	-41.07	13.24
90	-0.0217	0.5740	0.3080	-52.53	24.00	-46.40	-24.98
120	-0.0200	0.5753	0.3107	-59.20	18.67	-57.07	-32.53
180	-0.0177	0.5750	0.3200	-68.53	20.00	-94.40	-47.64

Mix ID: GPC7 (A35 S20 R2.5) Casting date: 20/07/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.317	1.325	0.8598				
14	0.316	1.325	0.856	5.333	0.000	16.533	7.289
21	0.318	1.328	0.858	-5.333	-12.000	7.200	-3.378
28	0.320	1.330	0.860	-10.667	-20.000	-2.133	-10.933
56	0.320	1.335	0.862	-10.667	-41.333	-7.467	-19.822
90	0.320	1.335	0.863	-13.333	-38.667	-14.133	-22.044
120	0.323	1.335	0.867	-25.333	-41.333	-28.800	-31.822
180	0.325	1.339	0.870	-33.333	-57.333	-40.800	-43.822

Mix ID: GPC9 (A35 S10 R1.5) Casting date: 29/06/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.1022	0.0554	0.1472	-	-	-	-
14	-0.126	0.051	0.141	93.867	18.933	26.133	46.31
21	-0.119	0.052	0.144	65.867	14.933	11.467	30.75
28	-0.118	0.055	0.147	61.867	2.933	2.133	22.31
56	-0.111	0.056	0.148	33.600	-3.733	-4.533	8.44
90	-0.101	0.058	0.152	-4.80	-11.73	-20.53	-12.35
120	-0.100	0.060	0.158	-8.80	-18.40	-41.87	-23.02
180	-0.099	0.065	0.163	-12.80	-38.40	-63.20	-38.13

Length Change test: SERIES-OPC

Mix ID: OPC1 Casting date: 02/08/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	0.0038	0.1014	0.0584	-	-	-	-
14	-0.0033	0.1040	0.0457	28.53	-10.40	50.93	23.02
21	-0.0123	0.0957	0.0393	64.53	22.93	76.27	54.57
28	-0.0153	0.0967	0.0377	76.53	18.93	82.93	59.46
56	-0.0163	0.0940	0.0323	80.53	29.60	104.27	71.47
90	0.0443	0.1583	0.0520	-162.13	-227.73	25.60	-121.42
120	0.0780	0.1730	0.0720	-312.00	-692.00	-288.00	-430.67
180	0.0980	0.1900	0.0900	-392.00	-760.00	-360.00	-504.00

Mix ID: OPC2 Casting date: 10/08/2012

Days	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)	Sample 1 (micro-strain)	Sample 2 (micro-strain)	Sample 3 (micro-strain)	Avg. (micro-strain)
7	-0.0252	-0.0866	-0.1738	-	-	-	-
14	-0.0320	-0.0960	-0.1800	27.200	37.600	24.800	29.860
21	-0.0353	-0.0977	-0.1823	40.533	44.267	34.133	39.640
28	-0.0477	-0.1047	-0.1843	89.867	72.267	42.133	68.080
56	-0.0243	-0.0847	-0.1633	-3.467	-7.733	-41.867	-17.680
90	-0.0107	-0.0727	-0.1337	-58.133	-55.733	-160.533	-91.467
120	0.0180	-0.0240	0.0100	-172.800	-250.400	-735.200	-386.133
180	0.0980	0.0010	0.0190	-492.800	-350.400	-771.200	-533.133

APPENDIX I: TEST FOR ALTERNATE WETTING AND DRYING.
Compressive strength test: SERIES-A (OVEN DRY)
Mix ID: SERIES A40 R2.5

Mix id		A40 S10 R1.5 (GPC3)			A40 S20 R1.5 (GPC4)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	485	62.25	59.5	545	69.95	68.25
	2	443.7	56.83		530	66.55	
90	1	468.5	60.13	61.3	545.5	69.32	70.2
	2	488.5	62.45		551.5	71.07	
180	1	508.4	64.99	62.9	561.2	71.74	72.3
	2	478.2	60.89		571.5	72.91	

Mix ID: SERIES A35 R2.5

Mix id		A35 S00 R2.5 (GPC5)			A40 S20 R2.5 (GPC6)		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	305.5	39.13	38.9	375	48.13	44.5
	2	301.5	38.77		325	40.81	
90	1	314.5	40.37	41.3	366.3	47.11	48.1
	2	328.3	42.31		385.6	49.10	
180	1	355.1	45.67	43.2	416.1	52.87	52.8
	2	320.1	40.76		379.1	47.79	

Mix ID: SERIES OPC

Mix id		OPC1			OPC2		
Days	**No**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**	**Load (kN)**	**Strength (MPa)**	**Avg. Strength (MPa)**
56	1	434.4	55.64	54.5	272.5	34.90	33.3
	2	418.8	53.54		249.1	31.84	
90	1	484.4	61.80	59.7	274.7	35.19	35.9
	2	452.1	57.56		288.1	36.76	
180	1	395.2	50.52	50.8	245.8	30.86	31.6

Compressive strength test: SERIES-A (AMBIENT DRY)

Mix id		A40 S10 R2.5 (GPC1)			A40 S10 R1.5 (GPC3)			A40 S20 R1.5 (GPC4)		
Days	No	Load (KN)	Strength (MPa)	Avg. Strength (MPa)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)	Load (kN)	Strength (MPa)	Avg. Strength (MPa)
56	1	339.5	42.97	46	363.8	46.88	48.3	495.5	62.96	62.2
	2	383.5	49.02		389.2	49.75		488.5	61.46	
90	1	392.2	50.24	48.6	430.9	55.19	55.4	550.5	70.37	68.3
	2	366	47.07		435.4	55.66		520.5	66.27	
180	1	382.5	48.90	49.8	510.5	65.65	64.9	569.5	73.39	71.8
	2	398.5	50.84		505.1	64.31		548.5	70.40	

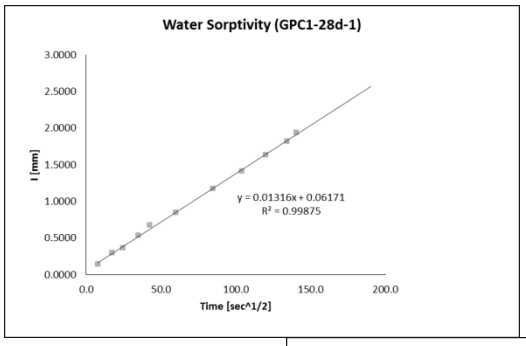
Mix id		A35 S00 R2.5 (GPC5)			A35 S10 R2.5 (GPC6)			A35 S20 R2.5 (GPC7)			A35 S10 R1.5 (GPC9)		
Days	No	Load (KN)	Strength (MPa)	Avg. Strength (MPa)	Load (KN)	Strength (MPa)	Avg. Strength (MPa)	Load (KN)	Strength (MPa)	Avg. Strength (MPa)	Load (KN)	Strength (MPa)	Avg. Strength (MPa)
56	1	225.5	28.94	28.5	263.5	33.48	32.8	337.9	43.46	42.5	272.5	34.83	33.6
	2	218.5	27.99		250.5	32.09		323	41.71		257.2	32.42	
90	1	251.5	31.96	33.1	295.6	37.94	37.2	332.8	41.79	43.6	336.5	43.02	42.4
	2	263.5	34.30		285.5	36.50		361.8	45.43		325.5	41.78	
180	1	267.5	34.26	34.7	325.5	40.63	41.7	335.5	42.97	46.9	345.2	43.86	44.5
	2	274.3	35.21		335.2	42.85		397.6	50.83		352.5	45.06	

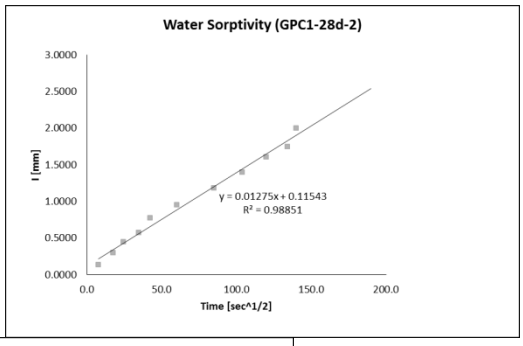
Mix id		OPC1			OPC2		
Days	No	Load (KN)	Strength (MPa)	Avg. Strength (MPa)	Load (KN)	Strength (MPa)	Avg. Strength (MPa)
56	1	415.6	52.81	55.2	302.6	38.61	39.3
	2	454.7	57.66		313.2	39.88	
90	1	465.6	59.28	58.8	327.5	42.29	41.5
	2	455.8	58.38		319.5	40.84	
180	1	480.5	61.06	56.5	280.2	35.89	35.6

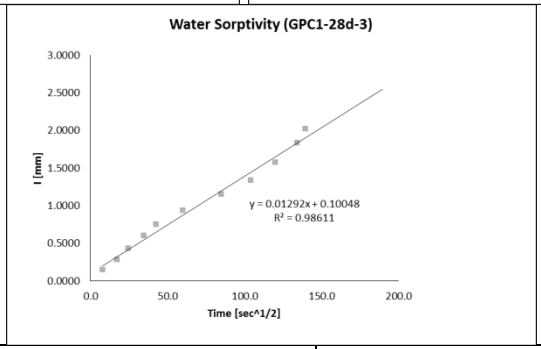
Mix Id	**GPC1 (A40 S10 R2.5)**	Test Age:	28 days
Casting Date	02/05/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.775	99.36	99.5
Average thickness	mm	51.6	51.33	50.033
Mass of conditioned specimens.	gm	934.81	926.56	911.23
Mass after sealing specimens.	gm	936.67	928.6	912.81
Exposed area	mm^2	7818.7	7754.8	7740.5

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	936.6	0	0	928.6	0	0	912.81	0	0
1 min	60	7.7	937.7	1.11	0.1420	929.65	1.05	0.1343	913.93	1.12	0.1432
5 min	300	17.3	938.9	2.29	0.2929	930.92	2.32	0.2967	914.98	2.17	0.2775
10 min	600	24.5	939.5	2.85	0.3645	932.05	3.45	0.4413	916.18	3.37	0.4310
20 min	1200	34.6	940.8	4.18	0.5346	933.05	4.45	0.5691	917.48	4.67	0.5973
30 min	1800	42.4	941.9	5.25	0.6715	934.62	6.02	0.7699	918.68	5.87	0.7508
1 hr	3600	60.0	943.2	6.58	0.8416	936	7.4	0.9464	920.1	7.29	0.9324
2 hr	7200	84.9	945.8	9.18	1.1741	937.82	9.22	1.1792	921.8	8.99	1.1498
3 hr	10800	103.9	947.6	11.01	1.4082	939.52	10.92	1.3967	923.25	10.44	1.3353
4 hr	14400	120.0	949.4	12.75	1.6307	941.15	12.55	1.6051	925.12	12.31	1.5744
5 hr	18000	134.2	950.8	14.22	1.8187	942.25	13.65	1.7458	927.11	14.3	1.8289
6 hr	19680	140.3	951.7	15.11	1.9325	944.2	15.6	1.9952	928.61	15.8	2.0208





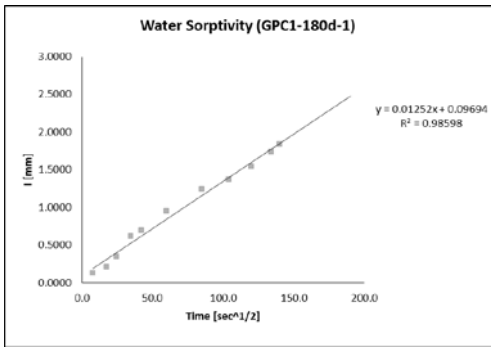


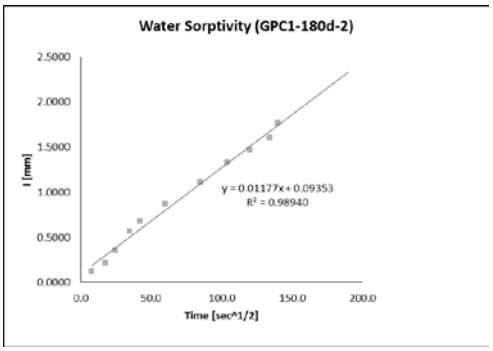
Mix Id	**GPC1 (A40 S10 R2.5)**	Test Age:	180 days

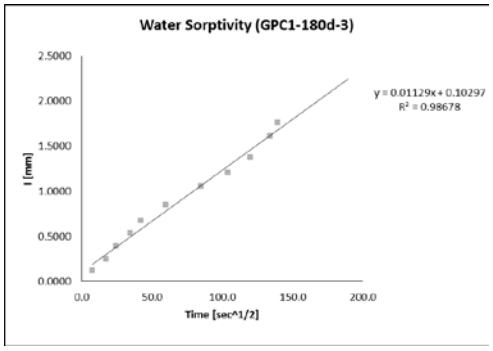
Casting Date	02/05/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	100.25	100.35	99.5
Average thickness	mm	50.6	50.8	51.03
Mass of conditioned specimens.	gm	876	846.5	873
Mass after sealing specimens.	gm	877.7	848.53	874.49
Exposed area	mm^2	7893.3	7909.1	7775.7

Time after initial contact		Sample 1				Sample 2			Sample 3		
Interval	Sec	Sec $^{1/2}$	Mass (gm)	Mass diff. (gm)	Absor-ption, I	Mass (gm)	Mass diff. (gm)	Absor-ption, I	Mass (gm)	Mass diff. (gm)	Absor-ption, I
0	0	0.0	877.7	0	0	848.53	0	0	874.49	0	0
1 min	60	7.7	878.7	1	0.1279	849.48	0.95	0.1215	875.45	0.96	0.1228
5 min	300	17.3	879.3	1.67	0.2136	850.22	1.69	0.2161	876.41	1.92	0.2456
10 min	600	24.5	880.4	2.75	0.3517	851.32	2.79	0.3568	877.53	3.04	0.3888
20 min	1200	34.6	882.5	4.86	0.6216	852.95	4.42	0.5653	878.67	4.18	0.5346
30 min	1800	42.4	883.1	5.46	0.6983	853.85	5.32	0.6804	879.77	5.28	0.6753
1 hr	3600	60.0	885.1	7.45	0.9528	855.32	6.79	0.8684	881.12	6.63	0.8480
2 hr	7200	84.9	887.4	9.7	1.2406	857.22	8.69	1.1114	882.75	8.26	1.0564
3 hr	10800	103.9	888.4	10.7	1.3685	858.92	10.39	1.3289	883.92	9.43	1.2061
4 hr	14400	120.0	889.8	12.1	1.5476	860.02	11.49	1.4696	885.24	10.75	1.3749
5 hr	18000	134.2	891.3	13.6	1.7394	861.05	12.52	1.6013	887.05	12.56	1.6064
6 hr	19680	140.3	892.1	14.4	1.8417	862.33	13.8	1.7650	888.21	13.72	1.7548





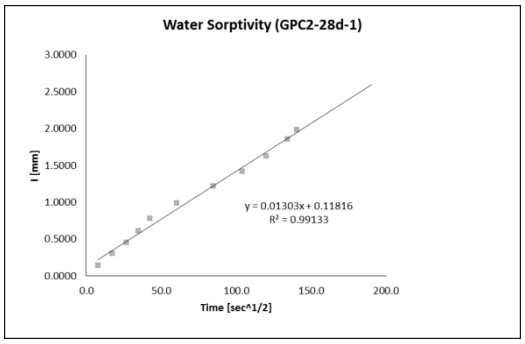


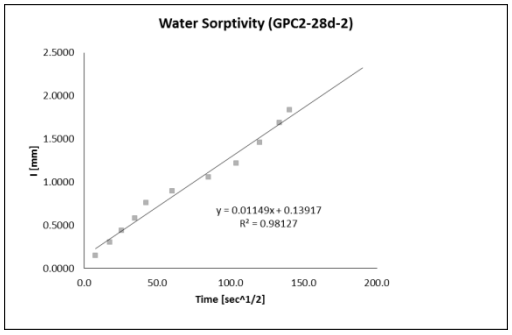
Mix id	GPC2 (A40 S20 R2.5)	Test Age:	28 days

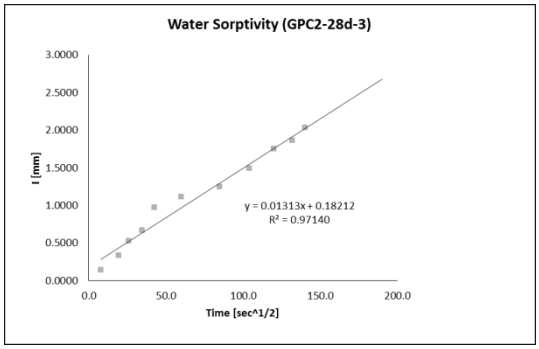
Casting Date	09/05/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.68	99.4	99.28
Average thickness	mm	50.4	52.05	52.33
Mass of conditioned specimens.	gm	926.2	942.75	951.45
Mass after sealing specimens.	gm	928.33	944.62	953.44
Exposed area	mm^2	7803.0	7760.0	7740.5

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	928.33	0	0	944.62	0	0	953.44	0	0
1 min	60	7.7	929.43	1.1	0.1407	945.78	1.16	0.1484	954.52	1.08	0.1381
5 min	300	17.3	930.68	2.35	0.3006	946.98	2.36	0.3018	956.02	2.58	0.3300
10 min	600	24.5	931.86	3.53	0.4515	948.05	3.43	0.4387	957.52	4.08	0.5218
20 min	1200	34.6	933.05	4.72	0.6037	949.15	4.53	0.5794	958.65	5.21	0.6664
30 min	1800	42.4	934.42	6.09	0.7789	950.54	5.92	0.7572	961.05	7.61	0.9733
1 hr	3600	60.0	936.05	7.72	0.9874	951.62	7	0.8953	962.15	8.71	1.1140
2 hr	7200	84.9	937.86	9.53	1.2189	952.89	8.27	1.0577	963.16	9.72	1.2432
3 hr	10800	103.9	939.42	11.09	1.4184	954.12	9.5	1.2150	965.08	11.64	1.4887
4 hr	14400	120.0	941.05	12.72	1.6269	956.02	11.4	1.4580	967.15	13.71	1.7535
5 hr	18000	134.2	942.85	14.52	1.8571	957.82	13.2	1.6883	968	14.56	1.8622
6 hr	19680	140.3	943.82	15.49	1.9811	958.98	14.36	1.8366	969.34	15.9	2.0336





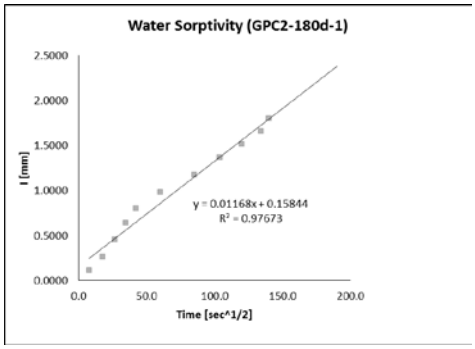


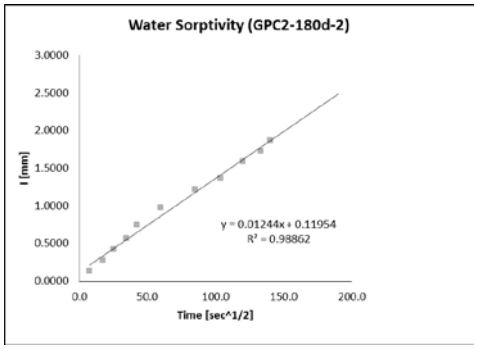
Mix Id	**GPC2 (A40 S20 R2.5)**	Test Age:	180 days

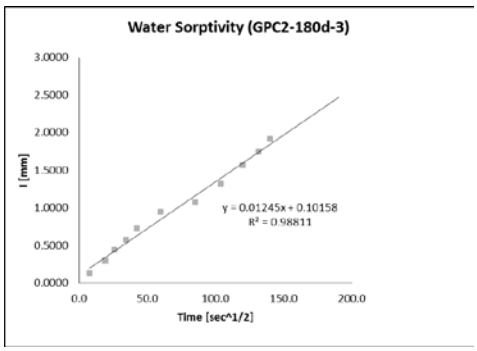
Casting Date	09/05/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.85	100.1	100.85
Average thickness	mm	51.4	51.5	51.33
Mass of conditioned specimens.	gm	862	886.1	873.2
Mass after sealing specimens.	gm	863.84	887.36	874.59
Exposed area	mm^2	7830.5	7869.7	7988.1

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	863.84	0	0	887.36	0	0	874.59	0	0
1 min	60	7.7	864.72	0.9	0.1126	888.39	1.03	0.1317	875.64	1.05	0.1343
5 min	300	17.3	865.92	2.1	0.2660	889.49	2.13	0.2724	876.89	2.3	0.2942
10 min	600	24.5	867.39	3.5	0.4540	890.63	3.27	0.4182	878.01	3.42	0.4374
20 min	1200	34.6	868.83	5.0	0.6382	891.78	4.42	0.5653	879.05	4.46	0.5704
30 min	1800	42.4	870.1	6.3	0.8006	893.2	5.84	0.7469	880.25	5.66	0.7239
1 hr	3600	60.0	871.52	7.7	0.9823	895.04	7.68	0.9823	881.95	7.36	0.9413
2 hr	7200	84.9	873	9.2	1.1716	896.92	9.56	1.2227	883.01	8.42	1.0769
3 hr	10800	103.9	874.52	10.7	1.3660	898.05	10.69	1.3672	884.91	10.32	1.3199
4 hr	14400	120.0	875.68	11.8	1.5143	899.78	12.42	1.5885	886.82	12.23	1.5642
5 hr	18000	134.2	876.78	12.9	1.6550	900.89	13.53	1.7305	888.19	13.6	1.7394
6 hr	19680	140.3	877.92	14.1	1.8008	901.97	14.61	1.8686	889.57	14.98	1.9159





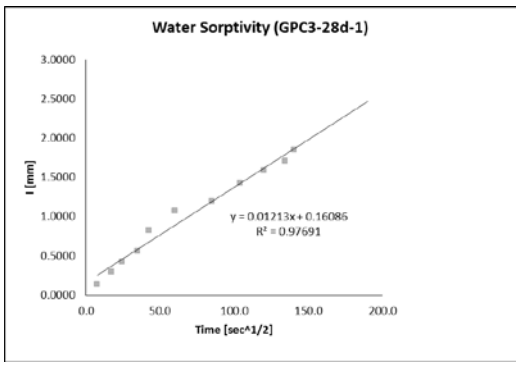


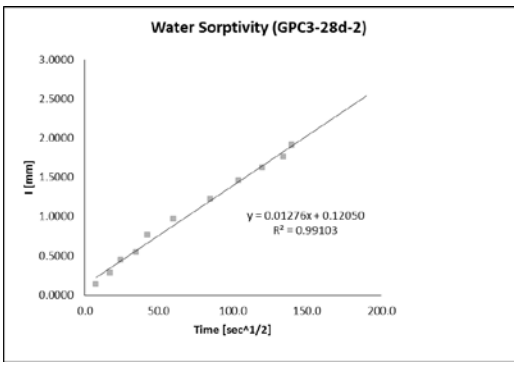
Mix Id	**GPC3 (A40 S10 R1.5)**	Test Age:	28 days

Casting Date	29/05/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2
Average diameter	mm	100.85	99.95
Average thickness	mm	50.2	49.8
Mass of conditioned specimens.	gm	889.1	835.11
Mass after sealing specimens.	gm	890.5	836.39
Exposed area	mm^2	7988.1	7846.1

Time after initial contact		**Sample 1**				**Sample 2**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	890.5	0	0	836.39	0	0
1 min	60	7.7	891.58	1.08	0.1381	837.48	1.09	0.1394
5 min	300	17.3	892.85	2.35	0.3006	838.59	2.2	0.2814
10 min	600	24.5	893.86	3.36	0.4297	839.92	3.53	0.4515
20 min	1200	34.6	894.93	4.43	0.5666	840.65	4.26	0.5448
30 min	1800	42.4	896.95	6.45	0.8249	842.38	5.99	0.7661
1 hr	3600	60.0	898.89	8.39	1.0731	843.95	7.56	0.9669
2 hr	7200	84.9	899.85	9.35	1.1959	845.98	9.59	1.2265
3 hr	10800	103.9	901.67	11.17	1.4286	847.83	11.44	1.4632
4 hr	14400	120.0	902.92	12.42	1.5885	849.1	12.71	1.6256
5 hr	18000	134.2	903.89	13.39	1.7126	850.15	13.76	1.7599
6 hr	19680	140.3	904.97	14.47	1.8507	851.38	14.99	1.9172

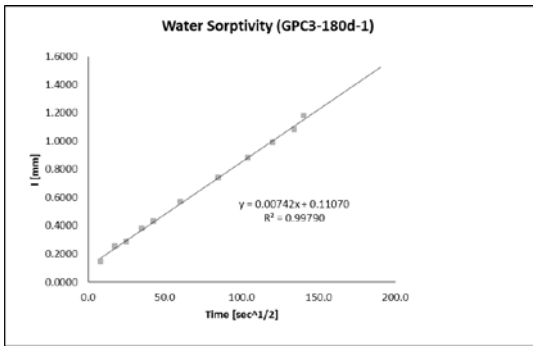


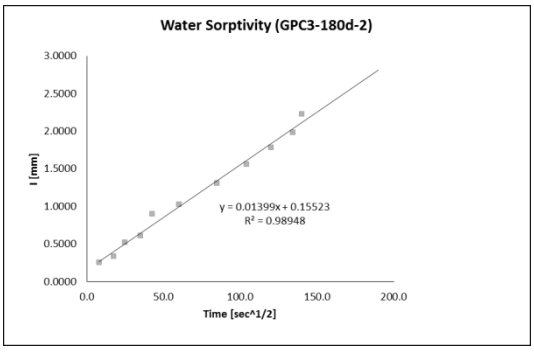


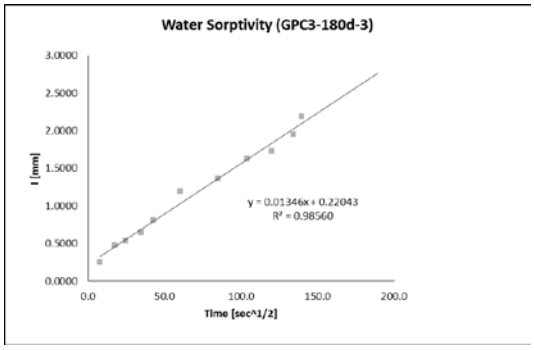
Mix Id	**GPC3 (A40 S10 R1.5)**	Test Age:	180 days
Casting Date	29/05/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	100.25	99.6	100.55
Average thickness	mm	51.6	51.8	49.03
Mass of conditioned specimens.	gm	837.25	854.21	835
Mass after sealing specimens.	gm	838.37	856.6	838.16
Exposed area	mm^2	7893.3	7791.3	7940.6

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	838.37	0	0	856.6	0	0	838.16	0	0
1 min	60	7.7	839.5	1.13	0.1445	858.55	1.95	0.2494	840.13	1.97	0.2520
5 min	300	17.3	840.36	1.99	0.2545	859.2	2.6	0.3325	841.89	3.73	0.4771
10 min	600	24.5	840.58	2.21	0.2827	860.64	4.04	0.5167	842.34	4.18	0.5346
20 min	1200	34.6	841.34	2.97	0.3799	861.35	4.75	0.6075	843.19	5.03	0.6433
30 min	1800	42.4	841.75	3.38	0.4323	863.6	7	0.8953	844.5	6.34	0.8109
1 hr	3600	60.0	842.81	4.44	0.5679	864.57	7.97	1.0194	847.52	9.36	1.1971
2 hr	7200	84.9	844.16	5.79	0.7405	866.83	10.23	1.3084	848.82	10.66	1.3634
3 hr	10800	103.9	845.26	6.89	0.8812	868.78	12.18	1.5578	850.87	12.71	1.6256
4 hr	14400	120.0	846.09	7.72	0.9874	870.52	13.92	1.7803	851.69	13.53	1.7305
5 hr	18000	134.2	846.83	8.46	1.0820	872.11	15.51	1.9837	853.42	15.26	1.9517
6 hr	19680	140.3	847.59	9.22	1.1792	874	17.4	2.2254	855.3	17.14	2.1922



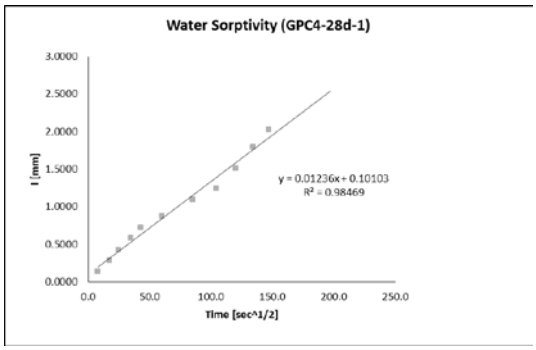


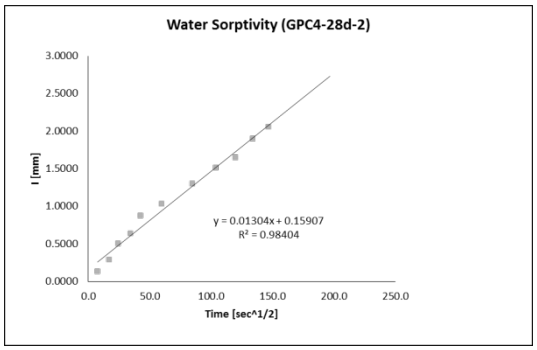


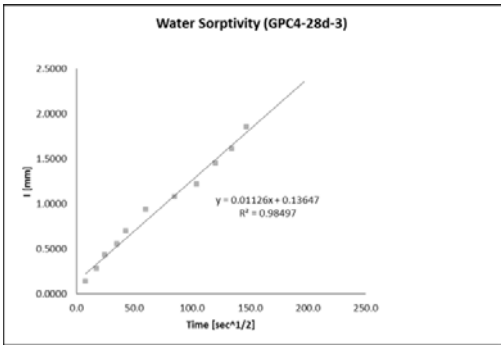
Mix Id	**GPC4 (A40 S20 R1.5)**	Test Age:	28 days
Casting Date	01/06/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.5	99.5	99.2
Average thickness	mm	50.1	49.2	47.1
Mass of conditioned specimens.	gm	881.7	881.35	830.4
Mass after sealing specimens.	gm	884.28	852.95	829.59
Exposed area	mm^2	7786.1	7775.7	7728.8

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	884.28	0	0	852.95	0	0	829.59	0	0
1 min	60	7.7	885.38	1.1	0.1407	853.98	1.03	0.1317	830.69	1.1	0.1407
5 min	300	17.3	886.52	2.24	0.2865	855.21	2.26	0.2891	831.78	2.19	0.2801
10 min	600	24.5	887.62	3.34	0.4272	856.89	3.94	0.5039	832.97	3.38	0.4323
20 min	1200	34.6	888.85	4.57	0.5845	857.92	4.97	0.6357	833.9	4.31	0.5512
30 min	1800	42.4	889.98	5.7	0.7290	859.8	6.85	0.8761	835.05	5.46	0.6983
1 hr	3600	60.0	891.09	6.81	0.8710	860.98	8.03	1.0270	836.89	7.3	0.9337
2 hr	7200	84.9	892.86	8.58	1.0974	863.1	10.15	1.2982	838	8.41	1.0756
3 hr	10800	103.9	894.02	9.74	1.2457	864.77	11.82	1.5118	839.1	9.51	1.2163
4 hr	14400	120.0	896.11	11.83	1.5130	865.85	12.9	1.6499	840.9	11.31	1.4465
5 hr	18000	134.2	898.3	14.02	1.7931	867.8	14.85	1.8993	842.2	12.61	1.6128
6 hr	19680	140.3	900.1	15.82	2.0234	869	16.05	2.0528	844.1	14.51	1.8558



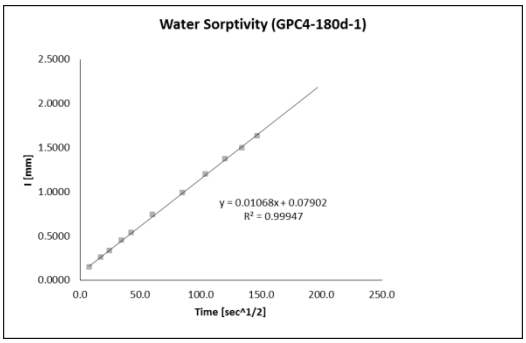


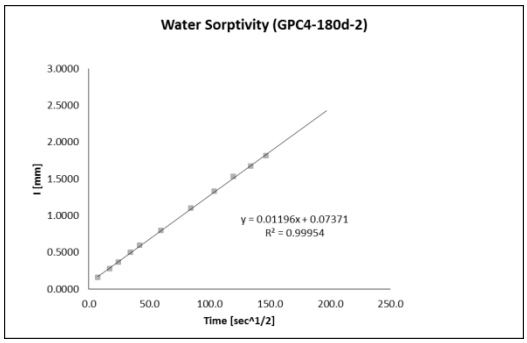


Mix Id	**GPC4 (A40 S20 R1.5)**	Test Age:	180 days
Casting Date	01/06/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2
Average diameter	mm	99.85	99.75
Average thickness	mm	51.1	48.2
Mass of conditioned specimens.	gm	869.2	921.2
Mass after sealing specimens.	gm	870.49	922.98
Exposed area	mm^2	7830.5	7814.8

Time after initial contact		**Sample 1**				**Sample 2**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	870.49	0	0	922.98	0	0
1 min	60	7.7	871.63	1.14	0.1458	924.16	1.18	0.1509
5 min	300	17.3	872.52	2.03	0.2596	925.13	2.15	0.2750
10 min	600	24.5	873.1	2.61	0.3338	925.81	2.83	0.3620
20 min	1200	34.6	874.03	3.54	0.4528	926.84	3.86	0.4937
30 min	1800	42.4	874.69	4.2	0.5372	927.6	4.62	0.5909
1 hr	3600	60.0	876.28	5.79	0.7405	929.2	6.22	0.7955
2 hr	7200	84.9	878.24	7.75	0.9912	931.56	8.58	1.0974
3 hr	10800	103.9	879.86	9.37	1.1984	933.35	10.37	1.3263
4 hr	14400	120.0	881.23	10.74	1.3736	934.93	11.95	1.5284
5 hr	18000	134.2	882.22	11.73	1.5003	936	13.02	1.6652
6 hr	19680	140.3	883.25	12.76	1.6320	937.13	14.15	1.8098

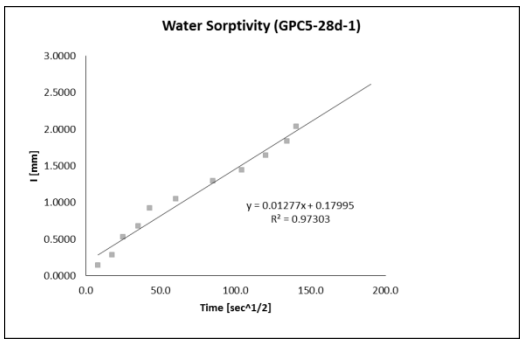


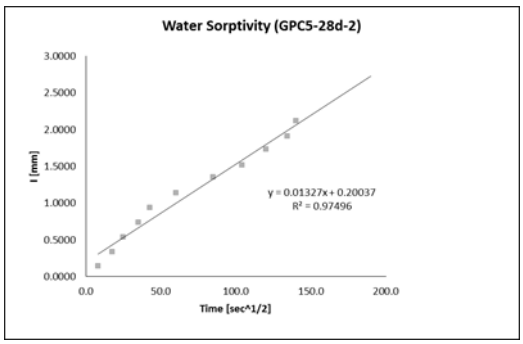


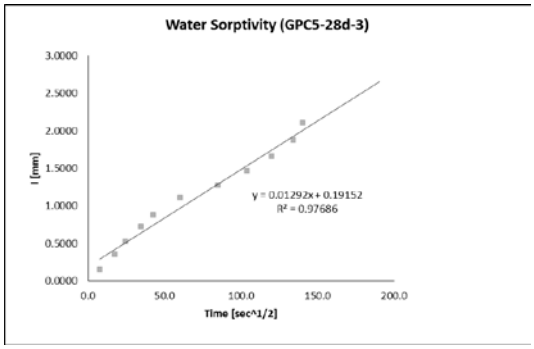
Mix Id	**GPC5 (A35 S00 R2.5)**	Test Age:	28 days
Casting Date	15/06/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	100.06	100.1	99.86
Average thickness	mm	51.6	51.33	50.03
Mass of conditioned specimens.	gm	863	866.25	835.21
Mass after sealing specimens.	gm	864.79	868.36	837.38
Exposed area	mm^2	7864.5	7869.7	7833.1

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	864.79	0	0	868.36	0	0	837.38	0	0
1 min	60	7.7	865.86	1.07	0.1369	869.45	1.09	0.1394	838.45	1.07	0.1369
5 min	300	17.3	866.97	2.18	0.2788	870.98	2.62	0.3351	839.89	2.51	0.3210
10 min	600	24.5	868.89	4.1	0.5244	872.52	4.16	0.5321	841.38	4	0.5116
20 min	1200	34.6	870.08	5.29	0.6766	874.09	5.73	0.7329	842.84	5.46	0.6983
30 min	1800	42.4	871.98	7.19	0.9196	875.68	7.32	0.9362	844.09	6.71	0.8582
1 hr	3600	60.0	872.98	8.19	1.0475	877.23	8.87	1.1345	845.52	8.14	1.0411
2 hr	7200	84.9	874.85	10.06	1.2867	878.89	10.53	1.3468	846.95	9.57	1.2240
3 hr	10800	103.9	876.05	11.26	1.4401	880.19	11.83	1.5130	848.21	10.83	1.3851
4 hr	14400	120.0	877.58	12.79	1.6358	881.89	13.53	1.7305	849.78	12.4	1.5859
5 hr	18000	134.2	879.09	14.3	1.8289	883.26	14.9	1.9057	850.98	13.6	1.7394
6 hr	19680	140.3	880.69	15.9	2.0336	884.87	16.51	2.1116	853.25	15.87	2.0298



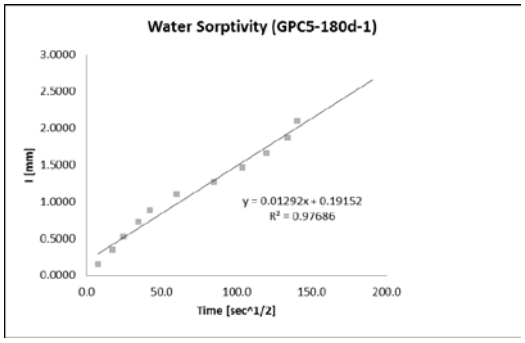


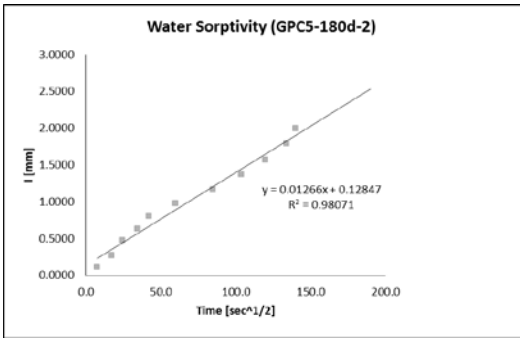


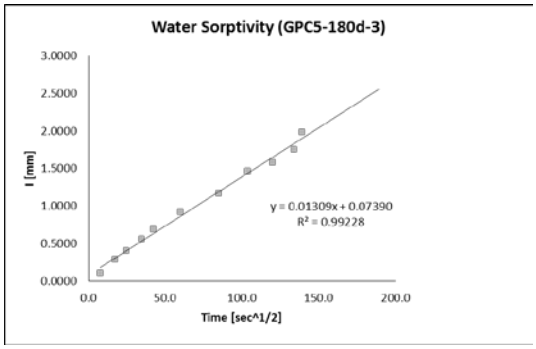
Mix Id	**GPC5 (A35 S00 R2.5)**	Test Age:	180 days
Casting Date	15/06/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.75	100.07	99.85
Average thickness	mm	50.5	50.3	49.8
Mass of conditioned specimens.	gm	856	845	835.21
Mass after sealing specimens.	gm	857.19	846.19	878.88
Exposed area	mm^2	7814.8	7865.0	7830.5

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	857.19	0	0	846.19	0	0	878.88	0	0
1 min	60	7.7	858.34	1.15	0.1471	847.09	0.9	0.1151	879.66	0.78	0.0998
5 min	300	17.3	859.89	2.7	0.3453	848.27	2.08	0.2660	881.09	2.21	0.2827
10 min	600	24.5	861.25	4.06	0.5193	849.87	3.68	0.4707	882.01	3.13	0.4003
20 min	1200	34.6	862.81	5.62	0.7188	851.15	4.96	0.6344	883.22	4.34	0.5551
30 min	1800	42.4	864.02	6.83	0.8735	852.49	6.3	0.8058	884.24	5.36	0.6855
1 hr	3600	60.0	865.81	8.62	1.1025	853.79	7.6	0.9720	886.06	7.18	0.9183
2 hr	7200	84.9	867.1	9.91	1.2675	855.3	9.11	1.1652	888.02	9.14	1.1690
3 hr	10800	103.9	868.6	11.41	1.4593	856.89	10.7	1.3685	890.32	11.44	1.4632
4 hr	14400	120.0	870.15	12.96	1.6576	858.47	12.28	1.5706	891.2	12.32	1.5757
5 hr	18000	134.2	871.78	14.59	1.8660	860.18	13.99	1.7893	892.58	13.7	1.7522
6 hr	19680	140.3	873.59	16.4	2.0975	861.79	15.6	1.9952	894.34	15.46	1.9773



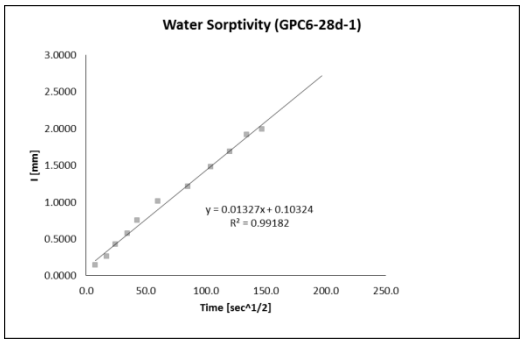


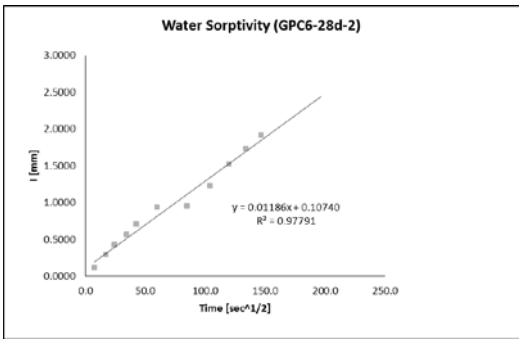


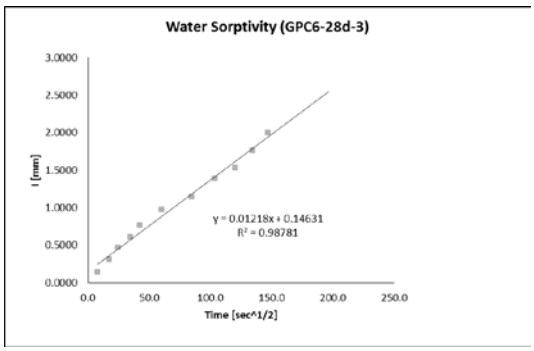
Mix Id	**GPC6 (A35 S10 R2.5)**	Test Age:	28 days
Casting Date	07/06/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.46	99.36667	99.5
Average thickness	mm	46.8	47.65	47.45
Mass of conditioned specimens.	gm	829.51	857.5	851.37
Mass after sealing specimens.	gm	831.58	855.59	853.37
Exposed area	mm^2	7770.4	7754.8	7775.7

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	831.58	0	0	855.59	0	0	853.37	0	0
1 min	60	7.7	832.68	1.1	0.1407	856.48	0.89	0.1138	854.48	1.11	0.1420
5 min	300	17.3	833.62	2.04	0.2609	857.89	2.3	0.2942	855.82	2.45	0.3134
10 min	600	24.5	834.89	3.31	0.4233	858.92	3.33	0.4259	857	3.63	0.4643
20 min	1200	34.6	836.08	4.5	0.5755	860	4.41	0.5640	858.12	4.75	0.6075
30 min	1800	42.4	837.48	5.9	0.7546	861.15	5.56	0.7111	859.34	5.97	0.7636
1 hr	3600	60.0	839.49	7.91	1.0117	862.89	7.3	0.9337	860.95	7.58	0.9695
2 hr	7200	84.9	841.03	9.45	1.2086	863.01	7.42	0.9490	862.31	8.94	1.1434
3 hr	10800	103.9	843.14	11.56	1.4785	865.2	9.61	1.2291	864.19	10.82	1.3839
4 hr	14400	120.0	844.75	13.17	1.6844	867.5	11.91	1.5233	865.3	11.93	1.5258
5 hr	18000	134.2	846.55	14.97	1.9146	869.1	13.51	1.7279	867.1	13.73	1.7560
6 hr	19680	140.3	847.12	15.54	1.9875	870.58	14.99	1.9172	868.98	15.61	1.9965



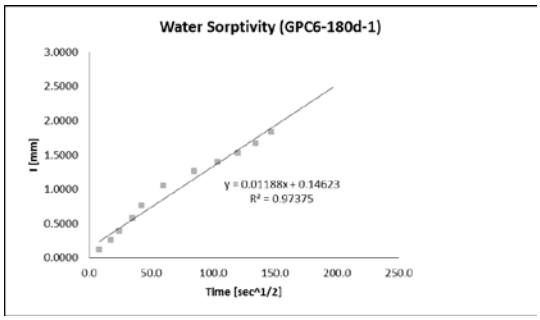


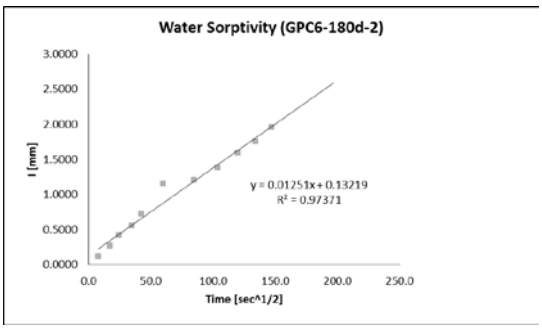


Mix Id	**GPC6 (A35 S10 R2.5)**	Test Age:	180 days
Casting Date	07/06/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2
Average diameter	mm	100.45	99.75
Average thickness	mm	49.65	48.55
Mass of conditioned specimens.	gm	866.1	834.51
Mass after sealing specimens.	gm	867.06	835.55
Exposed area	mm^2	7924.8	7814.8

Time after initial contact		**Sample 1**				**Sample 2**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	867.06	0	0	835.55	0	0
1 min	60	7.7	868	0.94	0.1202	836.48	0.93	0.1189
5 min	300	17.3	869.05	1.99	0.2545	837.68	2.13	0.2724
10 min	600	24.5	870.12	3.06	0.3914	838.86	3.31	0.4233
20 min	1200	34.6	871.56	4.5	0.5755	839.9	4.35	0.5564
30 min	1800	42.4	872.98	5.92	0.7572	841.25	5.7	0.7290
1 hr	3600	60.0	875.25	8.19	1.0475	844.6	9.05	1.1575
2 hr	7200	84.9	876.89	9.83	1.2572	845.02	9.47	1.2112
3 hr	10800	103.9	877.99	10.93	1.3979	846.39	10.84	1.3864
4 hr	14400	120.0	879	11.94	1.5271	848.02	12.47	1.5949
5 hr	18000	134.2	880.12	13.06	1.6704	849.32	13.77	1.7612
6 hr	19680	140.3	881.39	14.33	1.8328	850.87	15.32	1.9594

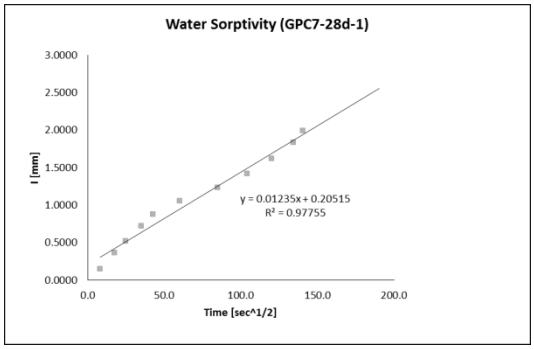


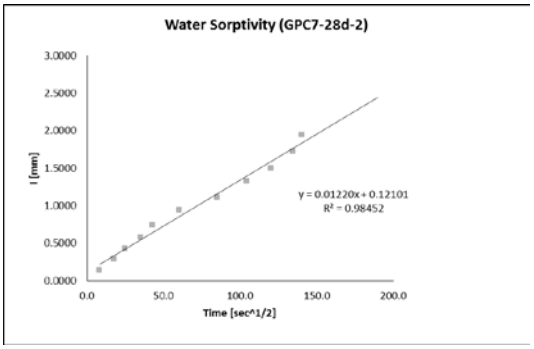


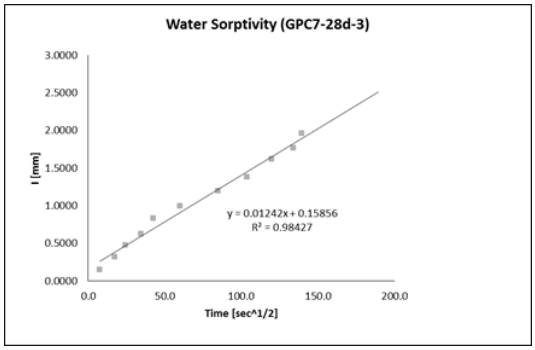
Mix Id	**GPC7 (A35 S20 R2.5)**	Test Age:	28 days
Casting Date	20/07/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.83	99.6	99.56
Average thickness	mm	51.6	51.33	50.03
Mass of conditioned specimens.	gm	838.25	843	806.21
Mass after sealing specimens.	gm	840.05	844.55	808.21
Exposed area	mm^2	7827.8	7801.7	7786.1

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	840.05	0	0	844.55	0	0	808.21	0	0
1 min	60	7.7	841.17	1.12	0.1432	845.64	1.09	0.1394	809.37	1.16	0.1484
5 min	300	17.3	842.86	2.81	0.3594	846.83	2.28	0.2916	810.68	2.47	0.3159
10 min	600	24.5	844.12	4.07	0.5205	847.92	3.37	0.4310	811.89	3.68	0.4707
20 min	1200	34.6	845.69	5.64	0.7213	849.05	4.5	0.5755	813.09	4.88	0.6241
30 min	1800	42.4	846.91	6.86	0.8774	850.37	5.82	0.7444	814.68	6.47	0.8275
1 hr	3600	60.0	848.26	8.21	1.0500	851.89	7.34	0.9388	815.98	7.77	0.9938
2 hr	7200	84.9	849.65	9.6	1.2278	853.24	8.69	1.1114	817.52	9.31	1.1907
3 hr	10800	103.9	851.12	11.07	1.4158	854.91	10.36	1.3250	819.02	10.81	1.3826
4 hr	14400	120.0	852.72	12.67	1.6205	856.25	11.7	1.4964	820.83	12.62	1.6141
5 hr	18000	134.2	854.39	14.34	1.8341	858.02	13.47	1.7228	822.03	13.82	1.7676
6 hr	19680	140.3	855.62	15.57	1.9914	859.75	15.2	1.9441	823.52	15.31	1.9581



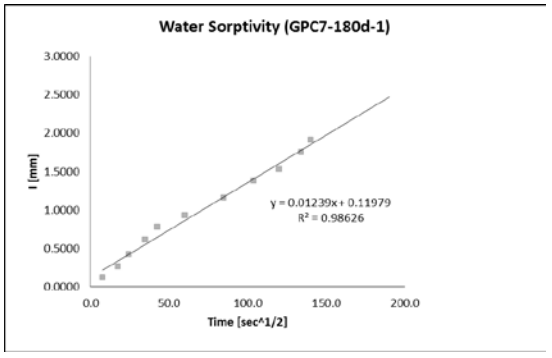


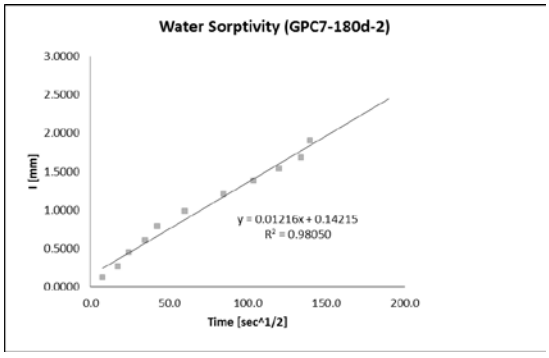


Mix Id	**GPC7 (A35 S20 R2.5)**	Test Age:	180 days
Casting Date	20/07/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2
Average diameter	mm	100.05	99.85
Average thickness	mm	50.6	50.3
Mass of conditioned specimens.	gm	840	833
Mass after sealing specimens.	gm	841.96	834.93
Exposed area	mm^2	7861.9	7830.5

Time after initial contact		**Sample 1**				**Sample 2**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	841.96	0	0	834.93	0	0
1 min	60	7.7	842.89	0.93	0.1189	835.88	0.95	0.1215
5 min	300	17.3	844.02	2.06	0.2635	837.01	2.08	0.2660
10 min	600	24.5	845.26	3.3	0.4221	838.39	3.46	0.4425
20 min	1200	34.6	846.74	4.78	0.6114	839.68	4.75	0.6075
30 min	1800	42.4	848.05	6.09	0.7789	841.08	6.15	0.7866
1 hr	3600	60.0	849.24	7.28	0.9311	842.64	7.71	0.9861
2 hr	7200	84.9	851.02	9.06	1.1588	844.35	9.42	1.2048
3 hr	10800	103.9	852.77	10.81	1.3826	845.75	10.82	1.3839
4 hr	14400	120.0	853.93	11.97	1.5309	846.95	12.02	1.5373
5 hr	18000	134.2	855.65	13.69	1.7509	848.07	13.14	1.6806
6 hr	19680	140.3	856.89	14.93	1.9095	849.8	14.87	1.9019

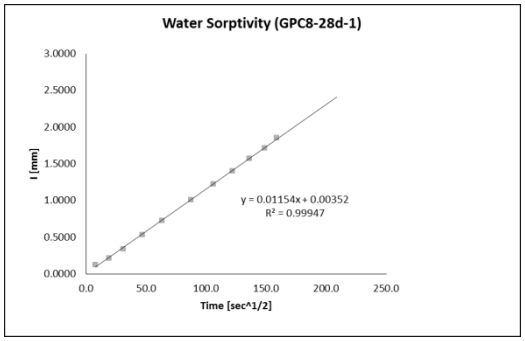


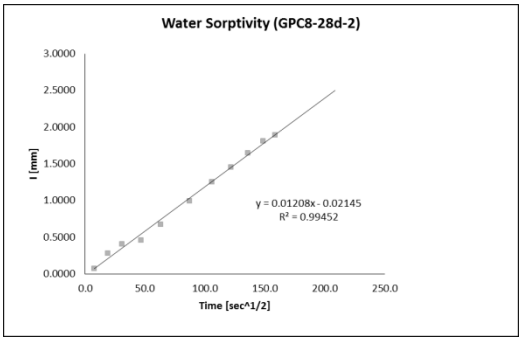


Mix Id	**GPC8 (A35 S00 R1.5)**	Test Age:	28 days
Casting Date	21/06/2012	Curing period:	28 days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.63	99.5	99.2
Average thickness	mm	46.45	46.5	48.4
Mass of conditioned specimens.	gm	825.8	820.1	842.1
Mass after sealing specimens.	gm	827.37	823.65	845.83
Exposed area	mm^2	7796.5	7775.7	7728.8

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	827.37	0	0	823.65	0	0	845.83	0	0
1 min	60	7.7	828.37	1	0.1279	824.24	0.59	0.0755	846.69	0.86	0.1100
5 min	300	17.3	829.06	1.69	0.2161	825.85	2.2	0.2814	847.57	1.74	0.2225
10 min	600	24.5	830.05	2.68	0.3428	826.82	3.17	0.4054	848.78	2.95	0.3773
20 min	1200	34.6	831.51	4.14	0.5295	827.25	3.6	0.4604	850.54	4.71	0.6024
30 min	1800	42.4	833.07	5.7	0.7290	828.9	5.25	0.6715	852.35	6.52	0.8339
1 hr	3600	60.0	835.25	7.88	1.0078	831.42	7.77	0.9938	855.06	9.23	1.1805
2 hr	7200	84.9	836.94	9.57	1.2240	833.42	9.77	1.2496	856.88	11.05	1.4133
3 hr	10800	103.9	838.33	10.96	1.4018	835.02	11.37	1.4542	858.35	12.52	1.6013
4 hr	14400	120.0	839.65	12.28	1.5706	836.52	12.87	1.6461	859.88	14.05	1.7970
5 hr	18000	134.2	840.79	13.42	1.7164	837.82	14.17	1.8123	861.17	15.34	1.9620
6 hr	19680	140.3	841.85	14.48	1.8520	838.42	14.77	1.8891	863.05	17.22	2.2024

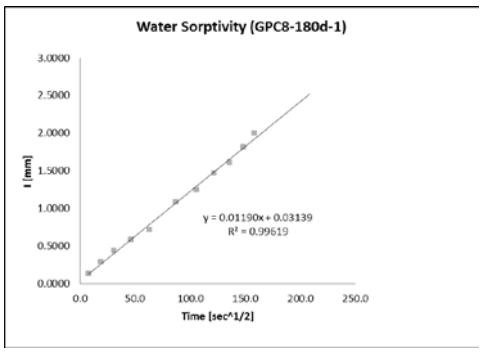


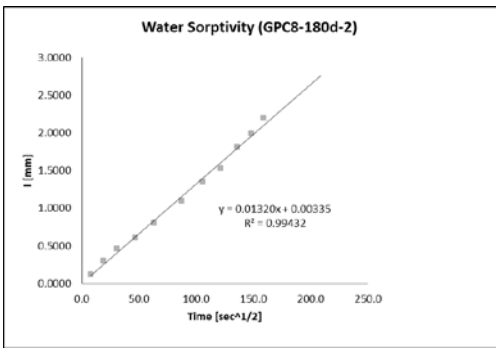


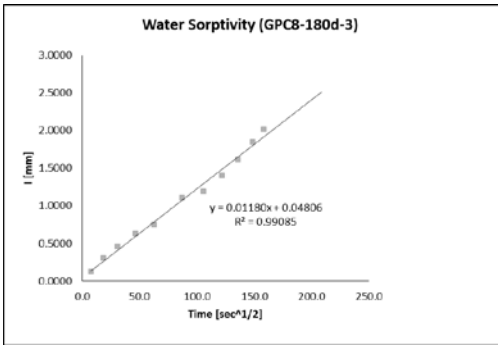
Mix Id	**GPC8 (A35 S00 R1.5)**	Test Age:	180 days
Casting Date	21/06/2012	Curing period:	180days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	100.15	99.85	100.05
Average thickness	mm	46.45	46.5	48.4
Mass of conditioned specimens.	gm	848.2	853	848.2
Mass after sealing specimens.	gm	849.44	854.34	849.33
Exposed area	mm^2	7877.6	7830.5	7861.9

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	849.44	0	0	854.34	0	0	849.33	0	0
1 min	60	7.7	850.48	1.04	0.1330	855.29	0.95	0.1215	850.3	0.97	0.1241
5 min	300	17.3	851.68	2.24	0.2865	856.68	2.34	0.2993	851.7	2.37	0.3031
10 min	600	24.5	852.82	3.38	0.4323	857.92	3.58	0.4579	852.9	3.57	0.4566
20 min	1200	34.6	853.98	4.54	0.5807	859.05	4.71	0.6024	854.25	4.92	0.6293
30 min	1800	42.4	855.02	5.58	0.7137	860.59	6.25	0.7994	855.18	5.85	0.7482
1 hr	3600	60.0	857.9	8.46	1.0820	862.92	8.58	1.0974	857.98	8.65	1.1063
2 hr	7200	84.9	859.2	9.76	1.2483	864.89	10.55	1.3493	858.65	9.32	1.1920
3 hr	10800	103.9	860.89	11.45	1.4644	866.29	11.95	1.5284	860.3	10.97	1.4030
4 hr	14400	120.0	862.02	12.58	1.6090	868.51	14.17	1.8123	861.98	12.65	1.6179
5 hr	18000	134.2	863.59	14.15	1.8098	869.89	15.55	1.9888	863.81	14.48	1.8520
6 hr	19680	140.3	865.02	15.58	1.9927	871.51	17.17	2.1960	865.1	15.77	2.0170



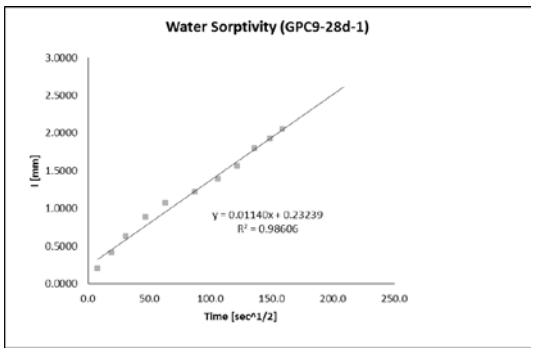


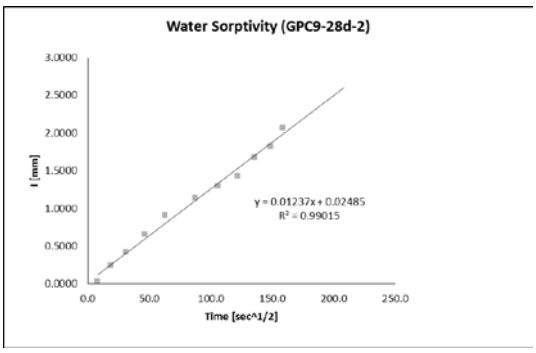


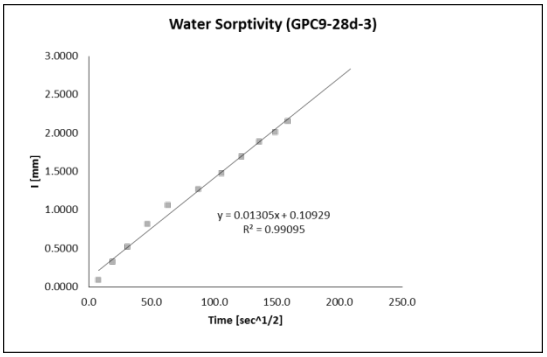
Mix Id	**GPC9 (A35 S10 R1.5)**	Test Age:	28 days
Casting Date	29/06/2012	Curing period:	28days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.63	99.5	99.2
Average thickness	mm	47.7	46.5	48.8
Mass of conditioned specimens.	gm	820.1	831.05	851.02
Mass after sealing specimens.	gm	822.04	833.77	853.14
Exposed area	mm^2	7796.5	7775.7	7728.8

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	822.04	0	0	833.77	0	0	853.14	0	0
1 min	60	7.7	823.61	1.57	0.2008	834.05	0.28	0.0358	853.81	0.67	0.0857
5 min	300	17.3	825.23	3.19	0.4080	835.68	1.91	0.2443	855.66	2.52	0.3223
10 min	600	24.5	826.91	4.87	0.6229	837.07	3.3	0.4221	857.2	4.06	0.5193
20 min	1200	34.6	828.94	6.9	0.8825	838.94	5.17	0.6612	859.53	6.39	0.8173
30 min	1800	42.4	830.41	8.37	1.0705	840.91	7.14	0.9132	861.4	8.26	1.0564
1 hr	3600	60.0	831.57	9.53	1.2189	842.69	8.92	1.1409	863.05	9.91	1.2675
2 hr	7200	84.9	832.87	10.83	1.3851	843.89	10.12	1.2943	864.67	11.53	1.4747
3 hr	10800	103.9	834.19	12.15	1.5540	844.98	11.21	1.4337	866.35	13.21	1.6895
4 hr	14400	120.0	836.08	14.04	1.7957	846.88	13.11	1.6768	867.86	14.72	1.8827
5 hr	18000	134.2	837.07	15.03	1.9223	848.03	14.26	1.8238	868.85	15.71	2.0093
6 hr	19680	140.3	838.05	16.01	2.0477	849.95	16.18	2.0694	869.98	16.84	2.1538



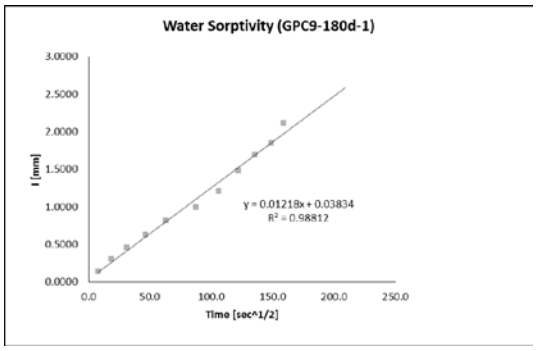


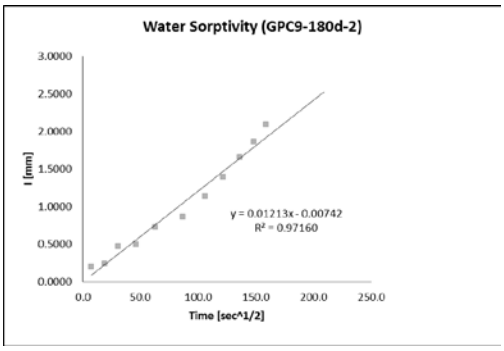


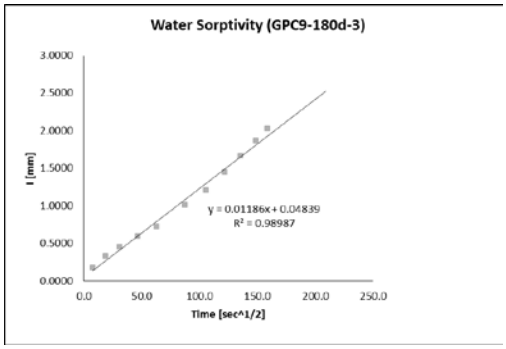
Mix Id	**GPC9 (A35 S10 R1.5)**	Test Age:	180 days
Casting Date	29/06/2012	Curing period:	180days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	100.05	99.9	99.9
Average thickness	mm	49.2	48.9	51.2
Mass of conditioned specimens.	gm	816	818	846
Mass after sealing specimens.	gm	817.59	819.28	847.48
Exposed area	mm^2	7861.9	7838.3	7838.3

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	817.59	0	0	819.28	0	0	847.48	0	0
1 min	60	7.7	818.7	1.11	0.1420	820.86	1.58	0.2021	848.86	1.38	0.1765
5 min	300	17.3	819.94	2.35	0.3006	821.12	1.84	0.2353	850.09	2.61	0.3338
10 min	600	24.5	821.2	3.61	0.4617	822.96	3.68	0.4707	851.02	3.54	0.4528
20 min	1200	34.6	822.53	4.94	0.6318	823.16	3.88	0.4962	852.17	4.69	0.5998
30 min	1800	42.4	823.97	6.38	0.8160	824.96	5.68	0.7265	853.13	5.65	0.7226
1 hr	3600	60.0	825.37	7.78	0.9951	826.02	6.74	0.8620	855.37	7.89	1.0091
2 hr	7200	84.9	827.04	9.45	1.2086	828.18	8.9	1.1383	856.91	9.43	1.2061
3 hr	10800	103.9	829.17	11.58	1.4811	830.2	10.92	1.3967	858.77	11.29	1.4440
4 hr	14400	120.0	830.8	13.21	1.6895	832.23	12.95	1.6563	860.5	13.02	1.6652
5 hr	18000	134.2	832.06	14.47	1.8507	833.83	14.55	1.8609	862.06	14.58	1.8648
6 hr	19680	140.3	834.14	16.55	2.1167	835.67	16.39	2.0963	863.35	15.87	2.0298



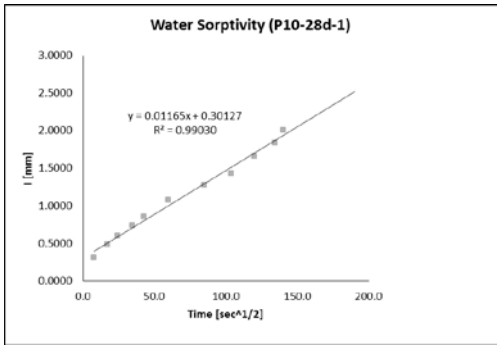


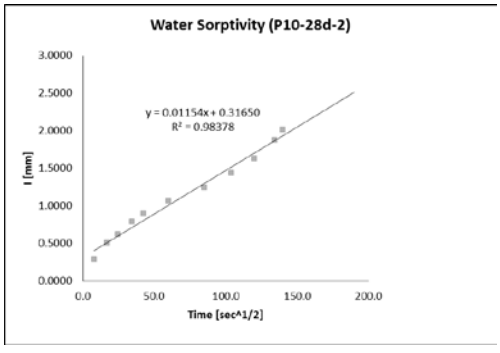


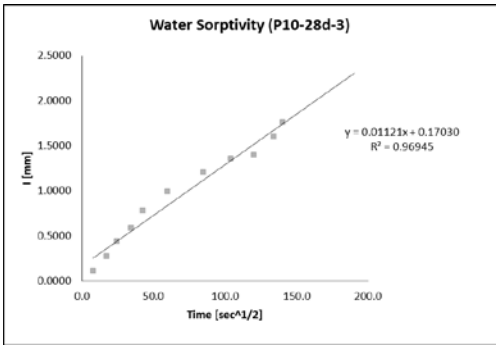
Mix Id	**GPC10 (A35 S20 R1.5)**	Test Age:	28 days
Casting Date	27/07/2012	Curing period:	28days

	Unit	Sample 1	Sample 2	Sample 3
Average diameter	mm	99.85	100.05	99.9
Average thickness	mm	51.6	51.33	50.03
Mass of conditioned specimens.	gm	838.25	848.58	837.2
Mass after sealing specimens.	gm	827.88	849.52	838.75
Exposed area	mm^2	7830.5	7861.9	7838.3

Time after initial contact		**Sample 1**				**Sample 2**			**Sample 3**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	827.88	0	0	849.52	0	0	838.75	0	0
1 min	60	7.7	830.33	2.45	0.3134	851.8	2.28	0.2916	841.22	2.47	0.3159
5 min	300	17.3	831.66	3.78	0.4835	853.47	3.95	0.5052	843.28	4.53	0.5794
10 min	600	24.5	832.59	4.71	0.6024	854.37	4.85	0.6203	844.28	5.53	0.7073
20 min	1200	34.6	833.66	5.78	0.7393	855.72	6.2	0.7930	845.48	6.73	0.8608
30 min	1800	42.4	834.55	6.67	0.8531	856.52	7	0.8953	846.26	7.51	0.9605
1 hr	3600	60.0	836.3	8.42	1.0769	857.83	8.31	1.0628	847.93	9.18	1.1741
2 hr	7200	84.9	837.89	10.01	1.2803	859.27	9.75	1.2470	850.35	11.6	1.4836
3 hr	10800	103.9	839.06	11.18	1.4299	860.72	11.2	1.4325	852.18	13.43	1.7177
4 hr	14400	120.0	840.85	12.97	1.6588	862.24	12.72	1.6269	853.46	14.71	1.8814
5 hr	18000	134.2	842.24	14.36	1.8366	864.15	14.63	1.8712	854.82	16.07	2.0553
6 hr	19680	140.3	843.58	15.7	2.0080	865.27	15.75	2.0144	855.85	17.1	2.1871







Mix Id	**GPC10 (A35 S20 R1.5)**	Test Age:	180 days
Casting Date	27/07/2012	Curing period:	180 days

	Unit	Sample 1	Sample 2
Average diameter	mm	99.85	100.05
Average thickness	mm	51.6	51.33
Mass of conditioned specimens.	gm	838.25	848.58
Mass after sealing specimens.	gm	827.88	849.52
Exposed area	mm^2	7830.5	7861.9

Time after initial contact		**Sample 1**				**Sample 2**		
Interval	**Sec**	**Sec $^{1/2}$**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**	**Mass (gm)**	**Mass diff. (gm)**	**Absor-ption, I**
0	0	0.0	827.88	0	0	849.52	0	0
1 min	60	7.7	830.33	2.45	0.3134	851.8	2.28	0.2916
5 min	300	17.3	831.66	3.78	0.4835	853.47	3.95	0.5052
10 min	600	24.5	832.59	4.71	0.6024	854.37	4.85	0.6203
20 min	1200	34.6	833.66	5.78	0.7393	855.72	6.2	0.7930
30 min	1800	42.4	834.55	6.67	0.8531	856.52	7	0.8953
1 hr	3600	60.0	836.3	8.42	1.0769	857.83	8.31	1.0628
2 hr	7200	84.9	837.89	10.01	1.2803	859.27	9.75	1.2470
3 hr	10800	103.9	839.06	11.18	1.4299	860.72	11.2	1.4325
4 hr	14400	120.0	840.85	12.97	1.6588	862.24	12.72	1.6269
5 hr	18000	134.2	842.24	14.36	1.8366	864.15	14.63	1.8712
6 hr	19680	140.3	843.58	15.7	2.0080	865.27	15.75	2.0144